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Optimization of environmental benefits and mathematical modeling of hybrid photovoltaic and coal power generation system in low carbon environment

Ying Liu[1,*]
[1] CHN ENERGY JIANGSU ELECTRIC POWER GROUP CO., LTD., Nanjing, Jiangsu, 210036, China
Corresponding authors: (e-mail: liuying19720318@126.com).

Abstract This paper constructs a load regulation model of coal-fired power station based on PID control algorithm. The linear combination of proportional, integral and differential simulates the inertial delay characteristics of the unit, and the grid control instruction is input as a step signal to realize the dynamic regulation of load. The joint operation model of photovoltaic + coal-fired power generation is proposed to integrate the multiple systems, and the coal-fired unit is used as a regulating power source to enhance the use of new energy. Measuring the carbon emission reduction effect through environmental benefit assessment indicators. Construct a decision model for the replacement of installed power generation units to provide decision support for the replacement of old units. Demonstrate the environmental benefit optimization ability of this paper's method through empirical analysis. The results show that greater corporate value can be realized by replacing more coal power installations with photovoltaic installations. The difference between the ideal value and negative ideal value of the city in the three environmental benefit indicators does not exceed 0.05, and the mixed load regulation method has sensitivity. Through the method of this paper regulating the proportion of PV installation increased by 13.92% to achieve the optimization of environmental benefits.

Index Terms PID control algorithm, load regulation, joint operation, environmental benefit assessment, power generation installation replacement

I. Introduction

With the rapid growth of energy demand in society, fossil energy is becoming scarce, and relying on fossil energy alone cannot meet the growing energy demand of society. At the same time, over-reliance on fossil energy can create environmental problems such as the greenhouse effect [1]. In order to reduce CO_2 emissions to cope with the increasing environmental problems, it is necessary to reduce the proportion of fossil energy in the electricity supply [2], [3]. To this end, countries have formulated policies and subsidies to promote the rapid development of new energy sources, in order to reduce the proportion of fossil energy to achieve energy saving and emission reduction, and set the corresponding targets [4]. For example, Germany has committed to reach at least 80% of new energy power supply in 2030 [5]. EU countries plan to reach 27% of power supply from renewable energy sources by 2030 [6]. Denmark plans to realize the power supply completely by new energy in 2050 [7]. China has also proposed a “dual-carbon” goal, committing to increase the proportion of non-fossil fuels in primary energy consumption to 25% by 2030 [8].

In terms of new energy, China's new energy power is mainly composed of wind power and solar power [9]. Under the support of policy guidance, the photovoltaic energy industry attaches increasing importance to solar power generation, the installed capacity of solar power generation is increasing, the energy supply system is gradually sound, and the photovoltaic industry has entered the peak stage. Overall, although the proportion of coal-fired power generation is decreasing year by year, the actual power generation capacity of coal-fired power generation is instead in a state of growth due to the growing demand for electricity [10]. In the future, coal-fired power generation will still be an important role in China's energy supply chain. New energy sources, on the other hand, have the inherent advantages of great environmental protection potential and energy potential, and will continue to be developed in the future [11]. Therefore, further organic integration of coal power energy storage and photovoltaic energy storage is needed in the new power system to build a coal power and photovoltaic linkage development structure, and to improve the quality and effectiveness of coal power resources and photovoltaic resources utilization.

In China, coal-fired power generation is widely distributed, with relatively mature technology and flexible regulation capability. It is a relatively ideal way to absorb and regulate PV through coal-fired power generation [12]. Liu, P and Trieb, F proposed a modeling algorithm for the wholesale conversion of a conventional coal-fired power plant into a thermal storage power plant that maintains the fixed capacity of the existing coal-fired generating units while utilizing photovoltaics to replace the associated fuel demand, improving system flexibility while reducing carbon emissions [13]. Wang, J analyzed in detail the performance of a coal-fired and renewable solar PV co-generation system and found that the photovoltaic (PV) conversion efficiency and levelized cost of energy (LCOE) of the system varied with collector area and load [14]. Han, Y et al. proposed a novel solar-assisted power generation (SAPG) system that combines nonconcentrating solar photovoltaic (PV) with a coal-fired power plant to realize low-cost and efficient hybrid solar/coal power generation [15]. Haiping, C et al. combined a concentrating photovoltaic/thermal (C-PV/T) module with a coal-fired power plant to construct a hybrid power generation system, which achieved a reduction of coal consumption by 11 g/kWh and an increase in total efficiency by 1.3% [16]. Liu, H et al. proposed a novel solar photovoltaic-assisted coal-fired power generation (PTCG) system that combines parabolic trough collectors and solar towers to achieve higher solar PV contribution and better cost-effectiveness compared to standalone SPCG or STCG systems [17]. Shagdar, E et al. mention a new mechanism of joint integration of solar PV and 300 MW coal-fired power plant to improve the performance and techno-economic feasibility of the system while reducing pollutant emissions by reducing coal consumption [18]. With the minimization of power plant construction cost or environmental pollution as the main optimization objectives, the above studies are committed to achieving the goals of cost and carbon emission reduction by vigorously constructing photovoltaic (PV) power systems and reducing the share of coal-fired power generation [19]. However, these measures ignore the fact that coal-fired power generation can be directly coupled with PV power generation on the supply side to improve the supply-side power stability [20], [21]. In the foreseeable future, it is still necessary to rely on coal-fired generating units to provide intermittent energy to realize a large proportion of access to the grid with PV [22]. And coal-fired power generation as a kind of power generation system with its own regulation ability, can be used as a direct participation in the regulation of photovoltaic power generation system, but also can be added to the energy storage system to further improve the system energy utilization [23], [24]. However, the feasibility of directly combining coal-fired power generation with PV power generation on the supply side through load regulation still needs to be further explored.

The improvement of the environmental pollution problem relies on the promotion of the use of clean new energy. This paper establishes a hybrid power generation system. Combining grid instructions and coal-fired power generation target loads, it realizes the increase of the proportion of new photovoltaic energy power supply, as well as the flexible application of traditional coal power. Combine the electric carbon factor to measure the carbon emission intensity, the low carbon benefit index to evaluate the environmental contribution of PV new energy, and the reduction value of air pollutant concentration to judge the emission reduction effect. Design a decision model for replacement of installed power generation capacity, combining economic parameters and carbon emission constraints to quantify the possibility of replacement. Analyze the value of power generation replacement from two dimensions: price and technology. Verify the effectiveness of this paper's regulation method through sensitivity analysis. Practicing urban power generation load regulation using hybrid power generation systems to determine the optimization of environmental benefits.

II. Technical analysis of optimization and modeling of environmental benefits of hybrid power generation systems

This chapter analyzes the optimization of power system load response effect and the improvement of environmental benefits. By constructing the load regulation model, new energy is effectively utilized to reduce the consumption of traditional energy and realize the optimization of environmental benefits. Combined with the decision-making model of power generation installation replacement, it calculates the necessary conditions for enterprises to replace new generating units.

II. A. Mathematical description of load response model

II. A. 1) Load regulation model for coal-fired power stations

Coal-fired power station is a large and complex power generation system, and its power output undergoes a complex process of heat and mass transfer. Therefore, the regulation of power supply from coal-fired power generation requires the coordinated operation of various components. This results in an inertial delay in the regulation process of the output power of coal-fired power generation. In order to simulate the coal-fired power generation regulation and the inertia delay in its regulation process. In this paper, based on the principle of PID controller, the load response process of coal-fired power generation is simulated by inputting actual data as grid-side commands.

The PID control algorithm has a wide application base and is a frequently used control law in analog control systems. At the same time, it is possible to implement this algorithm using software.PID is a linear controller that regulates the target value based on the control deviation from the given target value and the actual value available. The PID controller consists of three parts: the proportional link (P), the integral link (I), and the differential link (D), which are linearly combined to form the desired controller. The mathematical description is as follows:

The individual links via linear combination are of the form:

$$U(t)=k_p[r(t)-y(t)]+k_i\int[r(t)-y(t)]dt+k_d\,d[r(t)-y(t)]/dt \tag{1}$$

where, k_p – proportional link coefficients, k_i – integral link coefficients, k_d – differential link coefficient, $r(t)$ – the value of the target instruction, $y(t)$ – the existing actual value.

The values of the three coefficients are determined by the time constants of each of the three. The controller is converted by Laplace transform into the form of transfer function, i.e.:

$$G(s)=\frac{U(s)}{E(s)}=k_p+\frac{1}{T_i s}+T_d s=k_p+\frac{k_i}{s}+k_d s \tag{2}$$

where, T_i – proportional link time constant, T_d – differential link time constant.

Based on the principle of PID controller, this paper establishes a mathematical model to simulate the load regulation of coal-fired power plant under the grid command, i.e., each grid control command is regarded as a step signal, and the coal-fired power generation is regulated to the target load by load control. The load regulation model of the coal-fired power plant is established through the linear combination of the three PID control methods and the determination of the time constant. The mathematical description of the load change of the control process is as follows:

$$\begin{aligned}(\Delta P)_{ij}=&k_1\left[\left(P_{AGC,C}\right)_{ij}-\left(P_c\right)_{(i-1)j}\right]+k_2\frac{1}{T_1}\int_{t_{1j}}^{t_{ij}}\left[\left(P_{AGC,C}\right)_{ij}-\left(P_c\right)_{(i-1)j}\right]dt\\&+k_3\frac{1}{T_2}\frac{d\left[\left(P_{AGC,C}\right)_{ij}-\left(P_c\right)_{(i-1)j}\right]}{dt}\end{aligned} \tag{3}$$

$$(P_c)_{ij}=(P_c)_{(i-1)j}+(\Delta P)_{ij},\Delta P\le v_{r,\max} \tag{4}$$

where, T_1 – integral time constant, T_2 – differential time constant, $P_{AGC,C}$ – the load command given by the grid at a certain point in time, P_C – is the real-time load of the coal-fired unit, ΔP – the value of load regulation at the next moment, k_1,k_2,k_3 – are the linear control coefficients of the controller respectively, $v_{r,\max}$ – the large stabilized climbing rate of the coal-fired unit for the day, i – time in seconds, j – time in days.

II. A. 2) New Energy + Coal-fired Power Generation Joint Operation Model

Power sources with good regulation performance on the power supply side are combined with new energy sources for multiple power generation system mode generation, which can realize a significant increase in the penetration rate of wind power and photovoltaic. At the same time, the coal-fired unit installed capacity is huge, good flexibility, in scheduling new energy has great potential. At present, there have been through the use of coal-fired power generation flexibility in the grid side through the peak dispatch renewable energy mode. The rapid growth of new energy leads to limited grid-side scheduling capacity, so it is worth exploring how to make full use of the regulation capacity of coal-fired units and realize the effective use of new energy power through multiple power generation systems in the process of growing new energy power generation.

Relying on the concept of multi-energy co-generation, a multi-generation system of “new energy + coal power + energy storage system” is created to supply the power grid and meet the load demand. It can realize the purpose of making full use of new energy, increasing the proportion of new energy in the power grid, breaking through the limitations of the existing new energy power use, and realizing the flexible and efficient operation of power on the supply side. Integrate power stations/power systems in the region into a whole through power transmission, and then interact with the grid to improve the stability of power supply to maintain the safe operation of the grid. The multi-generation system contains an interactive transmission network for power transmission and information interconnection. Through intelligent interconnection and power transmission technologies, different forms of supply-side power plants such as wind farms, photovoltaic power systems, coal-fired power systems, and energy storage systems, as well as interconnections between the grid and different types of users on the user side, can be realized. The supply side and the demand side are connected through the control center of the multiple power generation system to realize the interaction between the supply side and the demand side. The main feature that distinguishes the concept of multi-energy complementarity is the decentralized nature of the geographical distribution. In a sense, this system can be regarded as an integrated and centralized management mode of regional power stations, which can effectively integrate various forms and characteristics in the region without structural modification of the power grid, implement cost-effective control of power generation and costs in the region, realize regional interconnection, integrate power into the power grid through the power transmission system and the information system, and to a certain extent, reduce the constraints of the geographic conditions and Improve power supply stability.

Unlike the operation mode of power plants running independently to respond to the grid, the operation mode of the multiple power generation system coupled with new energy, through the coal-fired power plant regulation as a regulating power source for wind power / photovoltaic power generation to regulate the output power of the system, and then further power to the grid. The new energy + coal-fired power co-generation system aims to achieve a stable supply of electricity by fully utilizing the flexibility potential of coal-fired power plants. In a multiple generation system, the total system command is constructed as a linear superposition of the target loads of each power plant. The target power of a coal-fired power plant is the target load of the system minus the actual power generated by the new energy source. Therefore, the grid command and the target output power of coal-fired power plants in the multifunctional power generation system after coupling wind power or photovoltaic power differ from the independent operation of coal-fired power generation.

Electricity-side instructions of the photovoltaic-coal multigeneration system and the target load of the coal-fired generation:

$$P_{AGC}^{W\&C}\begin{bmatrix} P_{1,1} & \cdots & P_{1,j} \\ \vdots & \ddots & \vdots \\ P_{i,1} & \cdots & P_{i,j} \end{bmatrix} = P_{AGC,C}\begin{bmatrix} P_{1,1} & \cdots & P_{1,j} \\ \vdots & \ddots & \vdots \\ P_{i,1} & \cdots & P_{i,j} \end{bmatrix} + P_{AGC,W}\begin{bmatrix} P_{1,1} & \cdots & P_{1,j} \\ \vdots & \ddots & \vdots \\ P_{i,1} & \cdots & P_{i,j} \end{bmatrix} \tag{5}$$

where, $P_{AGC}^{W\&C}$ -is the light-coal combined operation AGC instruction, $P_{AGC,C}$ -is the original AGC instruction for coal-fired power generation, $P_{AGC,W}$ - for wind power original AGC instruction.

$$ctP_{ct}^{W\&C}\begin{bmatrix} P_{1,1} & \cdots & P_{1,j} \\ \vdots & \ddots & \vdots \\ P_{i,1} & \cdots & P_{i,j} \end{bmatrix} = P_{AGC}^{W\&C}\begin{bmatrix} P_{1,1} & \cdots & P_{1,j} \\ \vdots & \ddots & \vdots \\ P_{i,1} & \cdots & P_{i,j} \end{bmatrix} - P_{W}\begin{bmatrix} P_{1,1} & \cdots & P_{1,j} \\ \vdots & \ddots & \vdots \\ P_{i,1} & \cdots & P_{i,j} \end{bmatrix} \tag{6}$$

where, $P_{ct}^{W\&C}$ -is the ideal power supply of coal-fired power generation in the light-coal multiple generation system, P_W - is the real-time supply power of wind power.

Grid-side command and target load of coal-fired generation in the light-fire multiple generation system:

$$P_{AGC}^{PV\&C}\begin{bmatrix} P_{1,1} & \cdots & P_{1,j} \\ \vdots & \ddots & \vdots \\ P_{i,1} & \cdots & P_{i,j} \end{bmatrix} = P_{AGC,C}\begin{bmatrix} P_{1,1} & \cdots & P_{1,j} \\ \vdots & \ddots & \vdots \\ P_{i,1} & \cdots & P_{i,j} \end{bmatrix} + P_{AGC,PV}\begin{bmatrix} P_{1,1} & \cdots & P_{1,j} \\ \vdots & \ddots & \vdots \\ P_{i,1} & \cdots & P_{i,j} \end{bmatrix} \tag{7}$$

where, $P_{AGC}^{PV\&C}$ - is the AGC instruction for the light-fired multiple generation system, $P_{AGC,C}$ - is the original AGC instruction for coal-fired power generation, $P_{AGC,W}$ - is the original AGC instruction for photovoltaic power plant.

$$P_{ct}^{PV\&C}\begin{bmatrix} P_{1,1} & \cdots & P_{1,j} \\ \vdots & \ddots & \vdots \\ P_{i,1} & \cdots & P_{i,j} \end{bmatrix} = P_{AGC}^{PV\&C}\begin{bmatrix} P_{1,1} & \cdots & P_{1,j} \\ \vdots & \ddots & \vdots \\ P_{i,1} & \cdots & P_{i,j} \end{bmatrix} - P_{PV}\begin{bmatrix} P_{1,1} & \cdots & P_{1,j} \\ \vdots & \ddots & \vdots \\ P_{i,1} & \cdots & P_{i,j} \end{bmatrix} \tag{8}$$

where $P_{ct}^{PV\&C}$ - is the ideal power supply for coal-fired power generation in the photovoltaic-fire multiple generation system, P_W - is the real-time power supply of photovoltaic power.

Through the coupling of new energy power plant and coal-fired power station grid power supply instructions, the power supply instructions of the multiple power generation system are obtained, and at the same time, the part of new energy power supply is cut to obtain the new power supply instructions of coal-fired power generation in the multiple power generation system. The coal-fired power station assumes the roles of both power supply and regulation in the process.

II. B. Indicators for assessing environmental benefits

II. B. 1) Electrocarbon factor

The electric carbon factor is an important indicator for assessing the carbon emission level of traditional energy sources and the environmental benefits of different power systems. The electric carbon factor κ_{CO_2} is used to characterize the share of traditional energy output in the context of electric carbon market synergy, which is defined as follows:

$$\kappa_{CO_2} = \frac{m_{CO_2} p_{cG}}{p_{total}} \tag{9}$$

where m_{CO_2} is the carbon emission per unit of conventional energy output; p_{CG} is the fossil energy generation capacity; and p_{total} is the total electricity generation capacity of all generating units. The higher the value of the electric carbon factor, the higher the carbon emission for the same total electricity generation capacity, and the worse the environmental benefits.

II. B. 2) Low carbon benefit index

(1) Low Carbon Benefit Index (LCBI) for renewable energy power clusters.

As an important indicator for assessing the decarbonization level and environmental friendliness of the power system, the low-carbon benefit index of renewable energy indicates the proportion of wind turbines and photovoltaic power generation in the total power generation capacity. Using the Low Carbon Benefit Index as an indicator, the difference in carbon emissions between conventional and renewable energy sources can be quantified, and the carbon reduction potential and environmental impact of the power system can be assessed. This index can provide a scientific basis for park decision makers to promote the application and promotion of sustainable energy. The low carbon efficiency index χ_{RES} of PV is calculated as

$$\chi_{RES} = \frac{E_{RES}\phi_{CO_2}}{C_{RES}^{sc} + C_{RES}^{fn} + C_{RES}^{om}} \tag{10}$$

where E_{RES} is the total annual power generation of renewable energy; C_{RES}^{fn} is the annual financial cost of the new energy device; C_{RES}^{sc} is the initial self-financing of the new energy device; C_{RES}^{om} is the annual operating cost of the new energy device; and ϕ_{CO_2} is the carbon emission reduction quality of the new energy unit. Carbon emission reduction quality per unit of new energy generation.

(2) Low carbon benefit index of energy storage device.

The low carbon benefit index of energy storage device χ_{ES} is the

$$\chi_{ES} = \frac{E_{ES}\phi_{CO_2}}{C_{ES}^{sc} + C_{ES}^{fn} + C_{ES}^{om}} \tag{11}$$

where E_{ES} is the annual total energy of the energy storage device; C_{ES}^{sc} is the initial self-financing of the energy storage device; C_{ES}^{fn} is the annual financial cost of the energy storage device; and C_{ES}^{om} is the annual operating cost of the energy storage device.

(3) Low carbon benefit index of electric vehicle charging.

The low-carbon benefit of EV charging refers to the amount of CO2 reduction induced by driving an EV compared to driving a fuel vehicle. Neglecting the difference in carbon dioxide emission intensity caused by the difference in the types of electric vehicles, its low carbon benefit index χ_{CS} is

$$\chi_{CS} = \frac{E_{CS}\left(\dfrac{\beta}{\alpha} - \phi_{CO_2}\right)}{C_{CS}^{sc} + C_{CS}^{fn} + C_{CS}^{om}} \tag{12}$$

where β is the carbon emission per kilometer of fuel vehicle driving; α is the electricity consumption per kilometer of electric vehicle driving.

II. B. 3) Reductions in air pollutant concentrations

Through renewable energy sources such as photovoltaic and wind power, and technologies such as energy storage, society can reduce its reliance on fossil fuels, reduce air pollutant emissions, and improve air quality. The air pollutant concentrations mainly include respirable and fine particulate matter, nitrogen oxides $\left(NO_x\right)$ and sulfur dioxide $\left(SO_2\right)$, which can be obtained from the regional air quality report of the project site.

II. C. Decision Modeling for Installed Power Generation Replacement

If the capacity of the new generating unit B approved for replacement is α times the capacity of the generating unit A being replaced, i.e.:

$$C_{AP_B}=\alpha C_{AP_A} \tag{13}$$

where C_{AP_A}, C_{AP_B} are the installed capacity of generating sets A, B respectively; α is the replacement multiplier of generating set capacity.

If the generating unit A is exchanged after t_A years of operation, the generating unit A is closed down and the generating unit B is opened up, the operating profit of the generating unit B for the t year after its opening up can be obtained by considering only the new generating unit B:

$$R_B=\begin{cases}\left(0.816P_{net}-25.162\dfrac{A_{Q_{scoal,B}}}{c_{re,B}}P_{re,B}-A_{C_{v,B}}\right) & \\ \cdot C_{AP_B}N_{hour,B} & T_{con,B}<t\le T_{con,B}+T_{oper,B} \\ -\left(1+r_{oper,B}\right)\left(1-r_{nrdepr,B}\right)\cdot\dfrac{V_{depr,B}}{N_{depr,B}} & \\ 0 & t\le T_{con,B}\end{cases} \tag{14}$$

where $c_{re,B}$ is the calorific value coefficient of raw coal used in the generating unit B; $A_{Q_{scoal,B}}$ is the average coal consumption of standard coal supplied by the generating unit B; $P_{re,B}$ is the price of raw coal used in the generating unit B; $A_{C_{v,B}}$ is the cost of electricity per unit of electricity other than the cost of fuel; and $N_{hour,B}$ is the annual power generation utilization hours of the generating unit B; $r_{oper,B}$ is the approximate ratio of the annual fixed operating cost of the generating unit B to the original value of the fixed assets; $r_{nrdepr,B}$, $V_{depr,B}$, $N_{depr,B}$ are the net residual value of fixed assets, production value of fixed assets, and production value of fixed assets, respectively. Net Fixed Asset Residual Value Ratio, Original Value of Production, Depreciable Life; $T_{con,B}$, $T_{oper,B}$ are the planned construction period and the planned operation period of the generating set B, respectively.

Since the new genset B is a replacement of the genset A, if the operating period of the genset A is not completed, the cost of its remaining years becomes the operating cost of the new genset B. Since the generating set A is shut down after replacement, no variable costs, maintenance costs, taxes, etc. are incurred, and only depreciation costs may be incurred. This results in the operating costs of Genset A borne by Genset B in the t th year after its opening:

$$C_{caddA,B}=\begin{cases}C_{depr,A}=\dfrac{V_{depr,A}}{N_{depr,A}}\left(1-r_{nrdepr,A}\right) & 0<t\le T_{oper,A}-t_A \\ 0 & t>T_{oper,A}-t_A\end{cases} \tag{15}$$

where $C_{depr,A}$ is the annual depreciation cost of the generating unit A; $V_{depr,A}$, $r_{nrdepr,A}$, $N_{depr,A}$ are the original value of the fixed assets of the unit of the generating unit A, the net salvage rate, and the depreciation life, respectively; $T_{oper,A}$ is the design of the generating unit A; t_A is the actual operating life of the generating unit A.

The replacement operating profit in the t th year after the commencement of construction of the generating unit B is:

$$R'_B=R_B-C_{caddA,B} \tag{16}$$

can be obtained from equations (13) to (15):

$$R'_B=\begin{cases}-\dfrac{V_{depr,A}}{N_{depr,A}}\left(1-r_{nrdepr,A}\right)1\le t\le T_{con,B}\\ \left(0.816P_{net}-\dfrac{25.162}{c_{re,B}}A_{Q_{scoal,B}}P_{re,B}-A_{C_{v,B}}\right)\cdot C_{AP_B}N_{hour,B}\\ -\left(1+r_{oper,B}\right)\left(1-r_{nrdepr,B}\right)\dfrac{V_{depr,B}}{N_{depr,B}}\\ -\dfrac{V_{depr,A}}{N_{depr,A}}\left(1-r_{nrdepr,A}\right)T_{con,B}<t\le T_{oper,A}-t_A\\ \left(0.816P_{net}-\dfrac{25.162}{c_{re,B}}A_{Q_{scoal,B}}P_{re,B}-A_{C_{v,B}}\right)\cdot C_{AP_B}N_{hour,B}\\ -\left(1+r_{oper,B}\right)\left(1-r_{nrdepr,B}\right)\dfrac{V_{depr,B}}{N_{depr,B}}T_{oper,A}-t_A<t\le T_{con,B}+T_{oper,B}\end{cases} \tag{17}$$

Power generation companies participating in the generation unit exchange must have an increase in profits, which leads to the decision-making judgment conditions for the generation unit exchange:

$$N_{PV_{0,B}}=\sum_{t=1}^{T_{con,B}+T_{oper,B}}\left(R'_B-R_A\right)\left(1+I_{RR_{0,B}}\right)^{-t} \tag{18}$$

where $I_{RR_{0,B}}$ is the minimum internal rate of return on coal units acceptable to the power producer; $N_{PV_{0,B}}$ is the initial annual net present value of the generating unit B replacing the generating unit A under the condition of $I_{RR_{0,B}}$, and the power producer will implement the alternative when $N_{PV_{0,B}}>0$. Option, when $N_{PV_{0,B}}=0$, the generating company will consider the alternative, and when $N_{PV_{0,B}}<0$, the generating company will not consider the alternative.

III. Optimization practice of environmental benefits of light-coal hybrid regulation power generation

This chapter analyzes the necessity of replacing the firm's installed generating capacity. The sensitivity of the hybrid regulation method is verified. The application of this paper's methodology to the optimization of urban hybrid generation and environmental benefits is investigated.

III. A. Validation of the need for replacement of installed power generation under carbon emission constraints

III. A. 1) Impact of prices on the value of different generation technologies under carbon emission constraints

To realize the target load regulation through the hybrid PV and coal power generation system, it is necessary to replace the existing power generation installation and increase the number of PV power generation installation. For this reason, this section verifies the necessity of the replacement of installed power generation under the carbon emission constraints of a low-carbon environment in terms of both price and technology.

Figure 1 shows the impact of electricity price on the value of different generation technologies. Since the efficiency of PV power is higher than that of coal power, here it is assumed that φe (technical efficiency of coal power) = 0.5 and φ_N (technical efficiency of PV power) = 0.8, and it is also assumed that the investment in carbon-emission technology (CCS) is made 25 years after the investment decision on power generation (t = 25), then keeping the other parameters unchanged, Fig. 1 is obtained. from the impact of electricity price on the value of different power generation technologies, it is shown firstly that, when the carbon emission is is free (C is the economic cost to be paid for carbon emissions, and free means C=0), the net value of coal power is greater than the net value of PV power when the price of electricity generation is at a relatively low level, but as the price increases, the value of PV power will eventually exceed the value of coal power. Moreover, the value of coal power is progressively lower than the value of PV power once the relevant authorities are charged for carbon emissions. This chapter assumes that the investor is myopic and that the investor invests when carbon emissions are free (C=0), but after investing, as a charge is started on carbon emissions, Figure 1 illustrates that the value of the firm will decrease from the (C=0) curve to the A_1A_2 segment (C=25). Further, investors will invest in CCS technologies due to the increase in the price of carbon emissions. And it is well known that investing in CCS technology, although it can reduce carbon dioxide emissions significantly, will inevitably make the efficiency of power generation decrease. Assuming that the technical efficiency declines to c=0.45, Figure 1 can see the obvious folding inflection at point A after investing in CCS, based on which, even if the policy gives a subsidy of 0.45, as seen in Figure 1, the decline in technical efficiency makes the value of coal power technology enterprises even lower, all other conditions being equal. Therefore, it can be initially judged that the enterprise value obtained by investing in coal power + carbon emission technology is lower than that obtained by directly investing in photovoltaic power generation technology.

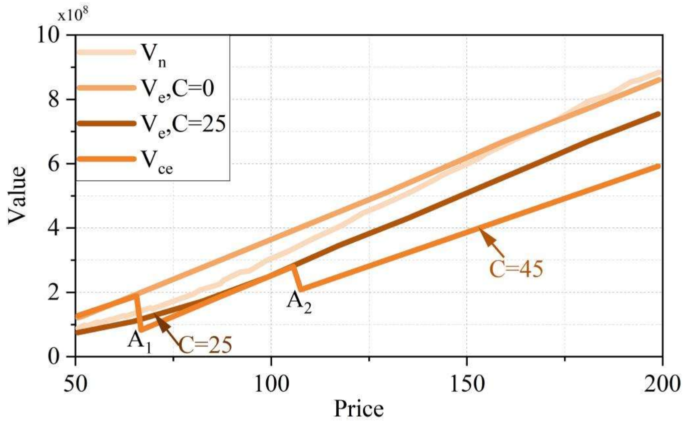

Figure 1: Influence of electricity price on the technical value of power generation

Figure 2 shows the impact of price uncertainty on different generation technologies. When price volatility increases from 0.03p in Figure 1 to 0.08p in Figure 2, it is clear from the comparison of Figures 1 and 2 that generation price uncertainty has a greater impact on PV electricity. Even if carbon emissions are free, the value of PV power technology is almost equal to that of coal power technology when the generation price is at a relatively low level. And as the price of generation increases, the value of PV power exceeds the value of coal power across the board, due to the fact that PV power has a higher technical efficiency N = 0.8 and PV power is utilized more efficiently. At the same price, this means greater output per unit of PV electricity, and at the same capacity, this means that PV electricity is more price-sensitive, so the higher the price, the faster the value of PV electricity rises than that of coal electricity.

The synthesis of Figures 1 to 2, combined with the reality of the situation, suggests that when CO2 is free to emit, and when electricity prices are at a relatively low level, coal power does indeed outweigh the value of PV power, which may be an important reason for the reality of coal power as the most dominant form of electricity generation. But in the severe situation of the climate problem, it seems that the carbon emission charge will be inevitable. Once the carbon charge is implemented, as the charge increases, Figure 1 illustrates that clean energy represented by photovoltaic power will outweigh traditional energy represented by coal power, so investment in coal power that ignores the carbon charge may be short-sighted, and coal power technology may have a strategic “technological value disadvantage” in the face of carbon-free clean energy technology. Therefore, it is necessary for companies to replace coal power generation with photovoltaic power generation under carbon emission constraints.

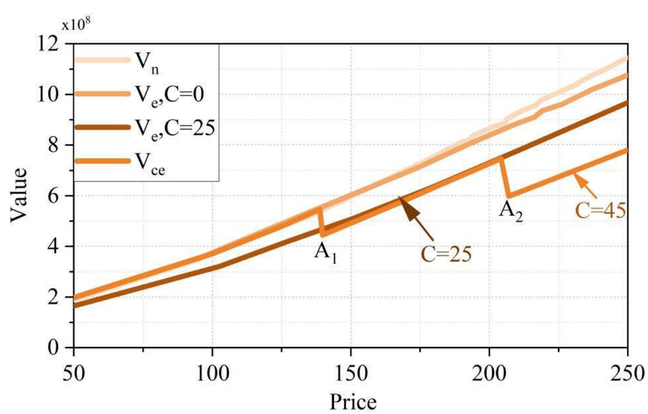

Figure 2: Impact of price uncertainty on power generation technology

III. A. 2) Impact of technical efficiency on the value of different power generation technologies

Figure 3 shows the effect of generation efficiency on the value of different technologies. Technical efficiency shows an increasing relationship with firm value, which is also consistent with intuitive understanding. So here, as an example, only the technical efficiency volatility φ_e of coal power generation is increased from 0.5 to 0.6, and other parameters are kept constant to obtain Figure 3.

Figure 3 first illustrates that advances in coal power technology increase investor value. As can be seen from the figure, when the price of carbon emissions is always relatively low (here assuming C=25), coal power companies will not invest in carbon emission technology, and the value of coal power technology may still be greater than the value of PV power technology even if a charge is imposed on carbon emissions, holding other parameters constant (paragraph A_1A_2). However at higher carbon prices (here assuming C=45), assuming that firms invest in carbon-emitting technologies (point A_2), the value of coal power is still greater than the value of PV power as long as the price of electricity generation is at a relatively low level. As the technical efficiency of photovoltaic power also shows an increasing relationship with the technical value, then its price sensitivity is higher, by Figure 3 is not difficult to imagine, when photovoltaic power technical efficiency is also improved under the premise (φe from 0.5 to 0.6, and φ_N is also from 0.8 to 0.9), as long as the price of electricity generation continues to rise, improve the efficiency of the technology of the coal power enterprise value will still be lower than that of the photovoltaic power enterprise value. Combined with the reality, Fig. 3 also illustrates that although investing in CCS technology brings about a reduction in carbon emissions, the decline in technical efficiency makes the coal power technology enterprise value even lower, and this result again shows why the relevant enterprises should gradually replace their coal power generation installations with PV power generation installations either at present or for a long period of time in the future.

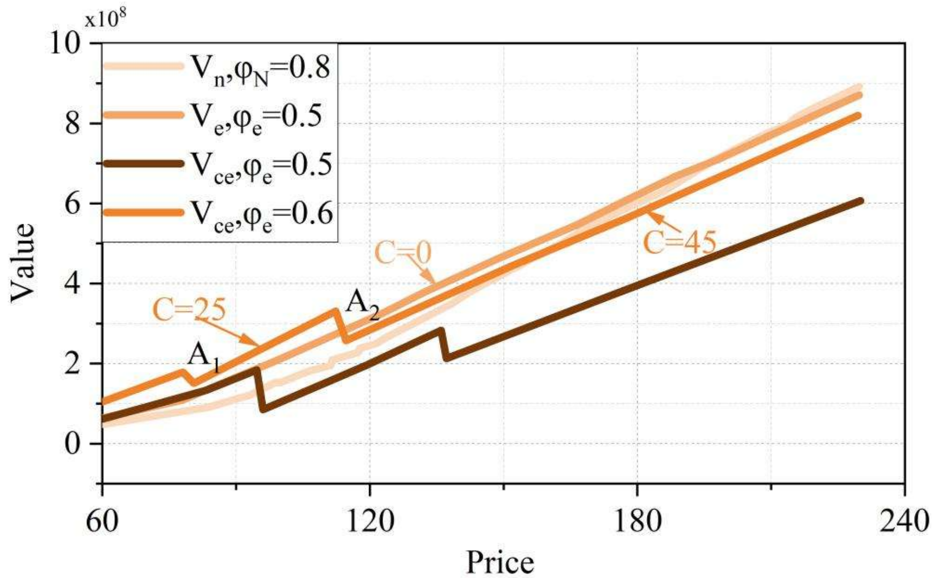

Figure 3: Influence of power generation efficiency on different technical values

III. B. Method sensitivity experiments and analysis of results

In order to assess the practical efficacy of the proposed load regulation method in hybrid PV+coal power projects, one such project in a city was selected for empirical study, and a corresponding experimental plan was developed and executed. Three PV plants with a total installed capacity of 15 MW and a design load of 270 MW, located in three different cities, were selected for the experiments, with a theoretically calculated average annual total solar radiation in the area where the plants are located, ranging from 1550 to 1800 kWh/m².

Relying on the data from this project, an in-depth assessment of the environmental benefits of low-carbon hybrid operation was carried out for these three cities using the proposed load regulation methodology. At the same time, the resulting indicators were subjected to a sensitivity specification process, from which selected indicators were used as the focus of the study. In view of the fact that load regulation methods may involve different indicator systems, we used the numbering system from A1 to A3 in our experiments to identify the electric carbon factor, the low carbon benefit index, and the reduction of air pollutant concentration to three environmental benefit indicators. With the help of EXCEL software, we calculated the maximum and minimum values of the sensitivity normalization matrix for each indicator. The experimental results show that the stability of the sensitivity is directly proportional to the environmental benefits: the more stable the values are, the better the environmental benefits perform. Therefore, the maximum value obtained from the experiment was defined as the ideal value, while the minimum value was considered as the negative ideal value. The difference between the two is used to quantify the performance strengths and weaknesses of the analyzed methods.

Table 1 shows the method analysis sensitivity results. Analyzing the data in Table 1 reveals that in the same scale of 15MW grid-connected PV+coal power project, the gap between the ideal and negative ideal values of the environmental benefit indicators of City 3 is tiny, with the differences of 0.016, 0.006, and 0.045 on the three indicators, which are not more than 0.05, which indicates that the range of variation of its environmental benefit indicators is relatively narrow, i.e., the sensitivity is stable. Therefore, deploying a 15MW PV plant in City 3 can generate significant environmental benefits, and the load regulation method we designed can effectively demonstrate the changes in environmental benefits of low-carbon operation of hybrid generation. However, the differences are 0.128, 0.162, and 0.141 for City 1 and 0.585, 0.424, and 0.266 for City 2. In contrast, the difference between the ideal and negative ideal values for City 1 and City 2 is significant. This implies that the actual environmental benefits of these two cities deviate significantly from the theoretical analysis and are less sensitive to the environmental benefits of low-carbon operation of hybrid generation. In addition, from a numerical point of view, the data obtained from the application of the method proposed in this study in City 3 are better than those in Cities 1 and 2, which are more in line with the actual situation, showing that our method is more accurate in the assessment of environmental benefits. To summarize, the proposed low-carbon operational load regulation method for hybrid power projects has higher sensitivity and its analysis results are more in line with real-world scenarios.

Table 1: Analyze the sensitive results of method

City label	Environmental benefit indicators	Ideal value	Negative ideal value	Difference
City 1	A1	0.515	0.387	0.128
	A2	0.636	0.474	0.162
	A3	0.492	0.351	0.141
City 2	A1	0.930	0.345	0.585
	A2	0.577	0.153	0.424
	A3	0.596	0.330	0.266
City 3	A1	0.642	0.626	0.016
	A2	0.793	0.787	0.006
	A3	0.686	0.641	0.045

III. C. Empirical analysis

III. C. 1) Installed capacity and power generation by power sources before and after planning

City 1 is used as an example to continue the in-depth study. In order to meet the growth of the overall power demand of City 1 in 2035, the load response model and the decision model for the replacement of installed power generation are comprehensively utilized, and combined with the environmental benefit assessment index, the planning and solving to obtain the expansion of the installed capacity of coal power and photovoltaic power in 2035. Table 2 shows the installed capacity and power generation of each power source before and after model planning. Analyzing the data in Table 2, the proportion of installed coal power decreased by 13.92%; the proportion of installed photovoltaic power increased by 13.92% due to the requirements of the clean energy development plan of City 1, and the total proportion is greater than 50%, which is dominant. It can be seen that after the model planning solution, City 1 uses more PV clean energy for power generation supply, and it is preliminarily judged that the city can achieve the optimization of environmental benefits by 2035.

Table 2: Installed capacity and power generation of each power source

Power supply type	2024		2035	
	Installed capacity(10^7kW)	Proportion(%)	Installed capacity(10^7kW)	Proportion(%)
Coal power	12.45	62.25	14.50	48.33
Photovoltaic	7.55	37.75	15.50	51.67
Proportion of new energy installed capacity (%)	37.75		51.67	
Total power generation(10^8kWh)	6593.46		9830.71	

III. C. 2) Comparative analysis of planning results

In order to investigate the differences in the power planning results of the hybrid generation system under different scenarios, this paper establishes the following five scenarios for the hybrid generation in City 1: Scenario 1: only the electro-carbon factor constraints are removed from the environmental benefit assessment; Scenario 2: only the low carbon benefit index constraints are removed from the environmental benefit assessment; Scenario 3: only the reduction value of air pollutant concentration constraints are removed from the environmental benefit assessment; Scenario 4: minimized generation cost; Scenario Scenario 4: minimize generation costs; Scenario 5: maximize generation costs.

Figure 4 shows the comparison of power planning results for scenarios 1–3. According to Fig. 4, the installed capacity of coal power is 14.50*10^7kW and that of PV is 15.50*10^7kW in the optimization result of integrated planning, and compared with the optimization result of Scenarios 1–3, the installed capacity of coal power is increased to 19.72, 17.33, and 18.77*10^7kW, and the installed capacity of PV is decreased to 10.28, 12.67, and 11.23*10^7kW. 10^7kW. It shows that under the scenario without considering the environmental benefits, the hybrid power generation system will rely more on the coal power units with lower cost in the short term, ignoring the subsequent cost of carbon emission, and failing to fully consider the rationality of the power structure. And there may also be a potential crisis of unstable power supply between generation and demand due to the reduced capacity of PV units.

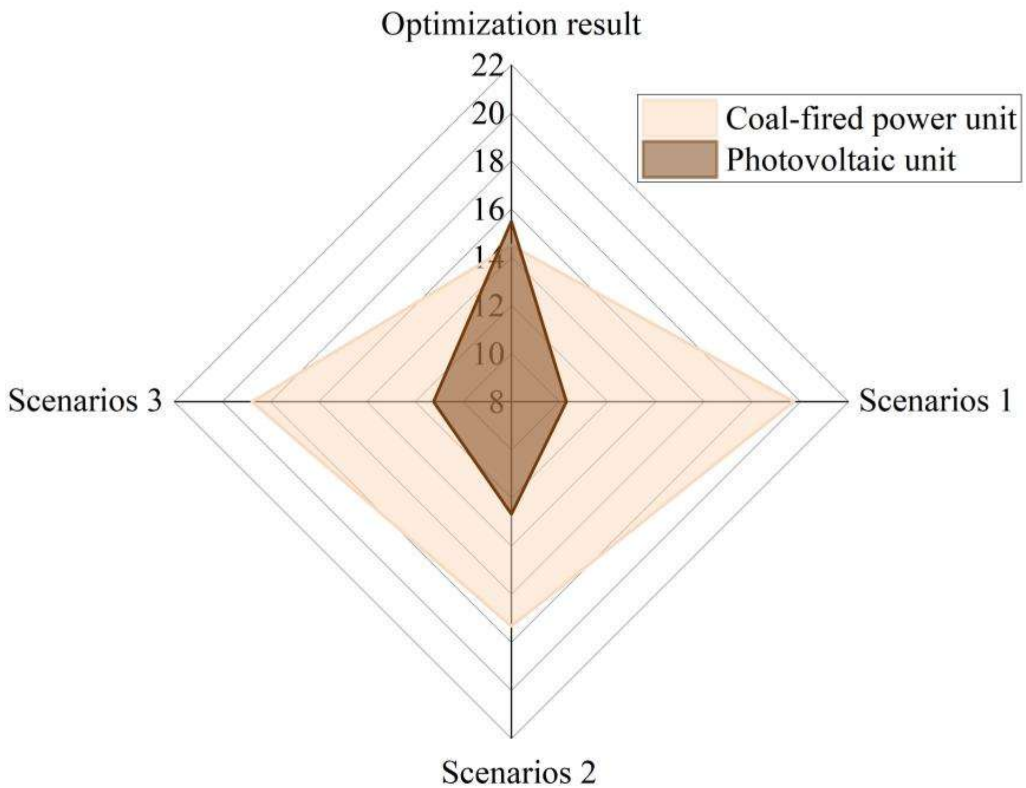

Figure 4: Comparison of power supply planning results in Scenarios 1–3

Further consideration is given to the impact of the cost of kWh on the optimization of the hybrid generation system. Figure 5 shows the comparison of the planning results for scenarios 4–5 power sources. The larger the difference between the degree cost of electricity of each power source, the more inclined the planning of the hybrid generation system is. The polarization of the kWh cost of coal and PV units becomes the minimized kWh cost scenario 0.25 (scenario 4) and maximized kWh cost scenario 0.95 (scenario 5), respectively. As we know from Fig. 5, under Scenario 4 minimized kWh cost, the installed capacity of the coal unit reaches 20.31*10^7kW while the installed capacity of the PV unit is only 9.69*10^7kW compared to the integrated optimization result, while under Scenario 5 maximized kWh cost, the installed capacity of the PV unit is 21.85*10^7kW and the coal unit is only 8.15*10^7kW. It indicates that in the case of lower cost of electricity price, more consideration will be given to increase the target load of coal units and decrease the usage of PV units. While in the case of higher electricity price, the usage of coal and PV units is opposite.

Taken together, a hybrid generation system would tend to use more coal-fired generation without considering environmental benefits and kWh costs. However, when combined with low-carbon targets, the use of coal and PV power is more balanced.

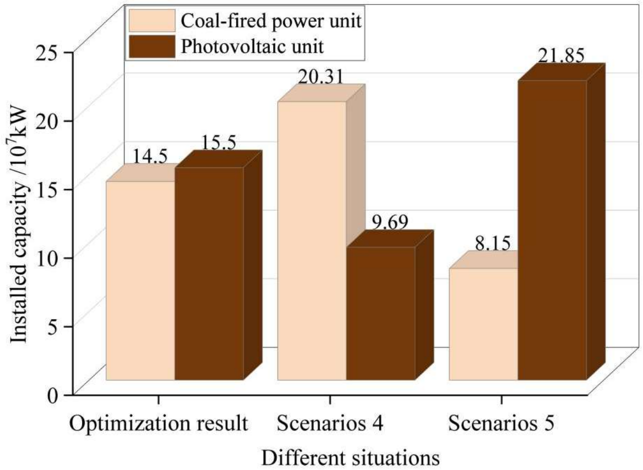

Figure 5: Comparison of power supply planning results in scenarios 4-5

IV. Conclusion

This paper constructs a PID load regulation model to realize hybrid operation of coal power + PV power generation and optimize the environmental benefits. The difference of urban environmental benefit index does not exceed 0.05, which proves the sensitivity of this paper's hybrid regulation-based power generation method. After planning using this paper's method, coal power dependence is reduced by 13.92%, while PV power usage is increased by a corresponding percentage. In extreme cases, the hybrid generation system still tends to use more coal power. In the future, the linkage analysis between the tariff policy and generation regulation can be strengthened to improve the winning odds of the game between environmental and economic benefits.

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