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OPTIMIZING ENVIRONMENTAL BENEFITS AND MODELING A HYBRID PHOTOVOLTAIC–COAL POWER SYSTEM IN A LOW-CARBON CONTEXT

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This study develops a load-adjustment model for a coal-fired power plant using a PID control approach, where proportional, integral, and derivative components are combined to represent unit inertia and delay, and grid dispatch commands are introduced as step inputs to enable dynamic load regulation. Building on this, a joint operating framework for a photovoltaic (PV)–coal hybrid system is proposed, using the coal unit as a flexible regulating source to improve renewable-energy utilization. Environmental benefit indicators are employed to quantify carbon-emission reduction performance, and a decision model is introduced to support the replacement of aging generation units. Empirical results suggest that substituting a larger share of coal capacity with PV can yield higher overall corporate value. Across three environmental benefit indicators, the gap between ideal and negative-ideal values for the evaluated city remains within 0.05, indicating sensitivity of the hybrid load-regulation strategy. Under the proposed method, increasing the PV installation share by 13.92% leads to improved environmental benefit outcomes.

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

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]. Prior studies have proposed multiple hybrid designs combining photovoltaics and coal plants [13, 14, 15, 16, 17, 18]. With the minimization of power plant construction cost or environmental pollution as the main optimization objectives, the above studies aim to achieve cost and carbon reduction by constructing photovoltaic systems and reducing the share of coal-fired generation [19]. However, these measures often ignore that coal-fired generation can be directly coupled with PV on the supply side to improve supply-side stability [20, 21]. In the foreseeable future, coal-fired units still provide intermittency support for large PV grid access [22]. Coal-fired generation can participate in regulation of PV systems and can be combined with storage to improve utilization [23, 24]. Yet the feasibility of directly combining coal-fired generation with PV via load regulation needs further exploration.

This paper establishes a hybrid power generation system. It uses grid instructions and coal-fired target loads to increase PV penetration while leveraging coal flexibility. Environmental benefit indicators include the electric carbon factor, low-carbon benefit index, and reductions in air pollutant concentrations. A decision model for installed unit replacement is built under economic parameters and carbon constraints. Sensitivity analysis and an empirical city case demonstrate optimization.

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.

Mathematical description of load response model

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 coal-fired output requires coordinated operation of components, resulting in inertial delay. To simulate this regulation and delay, this paper uses a PID controller and inputs actual grid-side commands.

PID is a linear controller that regulates the target value based on the control deviation between the setpoint and the actual value. The controller consists of proportional (P), integral (I), and differential (D) parts, linearly combined:

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

where k_p is the proportional coefficient, k_i the integral coefficient, k_d the differential coefficient, $r(t)$ the target instruction, and $y(t)$ the actual value.

After Laplace transform, the transfer function form is:

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

where T_i is the integral time constant and T_d is the differential time constant.

Each grid control command is treated as a step signal and the coal-fired unit is regulated toward the target load. The load regulation model is:

$$\Delta P_{ij}(k) = k_1\big(P_{AGC} - P_C\big) + \frac{k_2}{T_1}\int \big(P_{AGC} - P_C\big)\,dt + \frac{k_3}{T_2}\frac{d\big(P_{AGC} - P_C\big)}{dt}, \tag{3}$$

$$P_C(i,j) = P_C(i,j-1) + \Delta P_{ij}(k), \qquad \Delta P_{ij}(k) \le v_{r,\max} \ \text{(ramp constraint)}, \tag{4}$$

where T_1 is the integral time constant, T_2 the differential time constant, P_{AGC} is the grid command, P_C is the real-time load, ΔP is next-step adjustment, k_1, k_2, k_3 are linear control coefficients, and $v_{r,\max}$ is the maximum stabilized climbing rate. Index i is time (seconds) and j is time (days).

New Energy + Coal-fired Power Generation Joint Operation Model

A coupled multi-generation system can improve PV penetration while maintaining stability using coal flexibility. In a multi-generation system, the total command is a linear superposition of target loads; coal target power equals the system target minus real-time new-energy output.

For wind+coal, the multi-generation AGC instruction and coal target load can be expressed (matrix form) as:

$$P_{AGC}^{W\&C} = P_{AGC,C} + P_{AGC,W}, \tag{5}$$

$$P_{ct}^{W\&C} = P_{AGC}^{W\&C} - P_W, \tag{6}$$

where $P_{AGC}^{W\&C}$ is the wind-coal combined AGC instruction, $P_{AGC,C}$ coal original AGC, $P_{AGC,W}$ wind original AGC, $P_{ct}^{W\&C}$ ideal coal supply in the combined system, and P_W real-time wind supply.

For PV+coal:

$$P_{AGC}^{PV\&C} = P_{AGC,C} + P_{AGC,PV}, \tag{7}$$

$$P_{ct}^{PV\&C} = P_{AGC}^{PV\&C} - P_{PV}, \tag{8}$$

where $P_{AGC}^{PV\&C}$ is the PV-coal combined AGC instruction, $P_{AGC,PV}$ PV original AGC, $P_{ct}^{PV\&C}$ ideal coal supply, and P_{PV} real-time PV supply. Coal assumes both supply and regulation roles.

Indicators for assessing environmental benefits

Electrocarbon factor

The electric carbon factor κ_{CO_2} characterizes carbon intensity:

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

where m_{CO_2} is carbon emission per unit of conventional output, p_{CG} is fossil generation capacity, and p_{total} is total generation capacity. Higher κ_{CO_2} indicates worse environmental benefit.

Low carbon benefit index

(1) Renewable energy cluster LCBI:

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

where E_{RES} is annual renewable generation, C_{RES}^{fn} annual financial cost, C_{RES}^{sc} initial self-financing, C_{RES}^{om} annual operating cost, and ϕ_{CO_2} carbon reduction quality per unit generation.

(2) Energy storage LCBI:

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

(3) EV charging LCBI:

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

where β is carbon emission per km for fuel vehicles and α is electricity consumption per km for EVs.

Reductions in air pollutant concentrations

Air pollutant concentration reductions include PM, NO_x, and SO_2, obtained from regional air quality reports.

Decision Modeling for Installed Power Generation Replacement

If replacement unit B is α times the capacity of unit A:

$$C_B^{AP} = \alpha C_A^{AP}. \tag{13}$$

Considering only the new unit B, the operating profit in year t after commissioning is:

$$R_B(t) = \begin{cases} 0, & t \leq T_B^{con}, \\ \text{(revenue and cost terms per paper)}, & T_B^{con} < t \leq T_B^{con} + T_B^{oper}, \end{cases} \tag{14}$$

where parameters include coal calorific coefficient, coal consumption, coal price, other unit costs, annual utilization hours, fixed operating cost ratio, depreciation parameters, and construction/operation horizons (as defined in the paper).

If old unit A has remaining depreciation, its carried cost borne by B is:

$$C_{A\to B}^{add}(t) = \begin{cases} C_A^{depr}\left(1 - r_A^{nrdepr}\right), & 0 < t \leq T_A^{oper} - t_A, \\ 0, & t > T_A^{oper} - t_A, \end{cases} \tag{15}$$

where t_A is actual operating life of A.

Replacement operating profit:

$$R'_B(t) = R_B(t) - C_{A\to B}^{add}(t). \tag{16}$$

Decision condition via NPV under minimum acceptable internal rate of return $IRR_{0,B}$:

$$NPV_{0,B} = \sum_{t=1}^{T_B^{con}+T_B^{oper}} \frac{R'_B(t)}{(1+IRR_{0,B})^t} - I_{0,B}. \tag{18}$$

If $NPV_{0,B} > 0$, replacement is implemented; if $= 0$, considered; if < 0, not considered.

OPTIMIZATION PRACTICE OF ENVIRONMENTAL BENEFITS OF LIGHT-COAL HYBRID REGULATION POWER GENERATION

This chapter analyzes the necessity of replacing installed capacity, validates sensitivity, and studies an urban hybrid generation case.

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

Impact of prices on the value of different generation technologies under carbon emission constraints

Figure 1 shows the impact of electricity price on technology value. With $\phi_e = 0.5$ (coal) and $\phi_N = 0.8$ (PV), and CCS investment at $t = 25$, PV eventually exceeds coal as electricity price rises, especially when carbon is priced. Investing in CCS reduces technical efficiency (e.g., to 0.45), lowering coal value further.

Figure 2 shows price uncertainty effects; higher volatility increases PV sensitivity and raises PV value relative to coal.

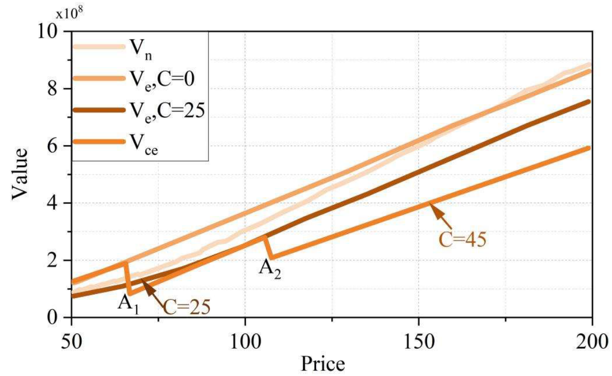

Figure 1: Influence of electricity price on the technical value of power generation.

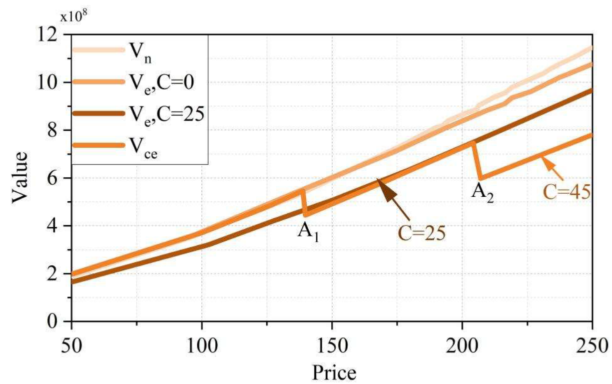

Figure 2: Impact of price uncertainty on power generation technology.

Impact of technical efficiency on the value of different power generation technologies

Figure 3 shows higher technical efficiency increases value. Even with improved coal efficiency, CCS-induced efficiency loss and PV improvements suggest PV replacement remains advantageous as prices rise.

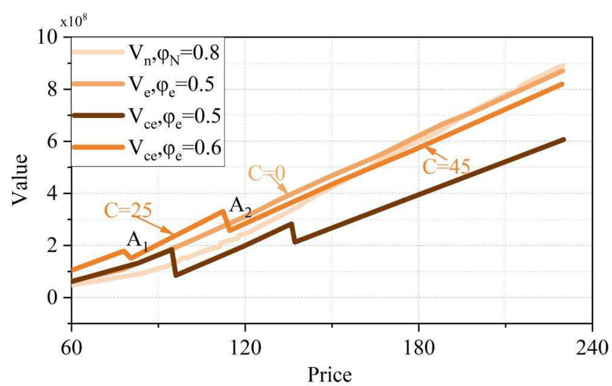

Figure 3: Influence of power generation efficiency on different technical values.

Method sensitivity experiments and analysis of results

A project with three cities (three PV plants total 15 MW; design load 270 MW) is used. Indicators are labeled A1 (electric carbon factor), A2 (low carbon benefit index), and A3 (air pollutant concentration reduction). The maximum is defined as ideal value and minimum as negative ideal value.

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
City 1	A2	0.636	0.474	0.162
City 1	A3	0.492	0.351	0.141
City 2	A1	0.930	0.345	0.585
City 2	A2	0.577	0.153	0.424
City 2	A3	0.596	0.330	0.266
City 3	A1	0.642	0.626	0.016
City 3	A2	0.793	0.787	0.006
City 3	A3	0.686	0.641	0.045

Empirical analysis

Installed capacity and power generation by power sources before and after planning

City 1 is used as an example. Table 2 shows that by 2035, coal installed proportion decreases by 13.92% and PV increases by 13.92%, with PV becoming dominant.

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

Power supply type	2024		2035	
	Installed capacity (10^7 kW)	Proportion (%)	Installed capacity (10^7 kW)	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 (%)			2024: 37.75 2035: 51.67	
Total power generation (10^8 kWh)			2024: 6593.46 2035: 9830.71	

Comparative analysis of planning results

Scenarios: (1) remove electro-carbon factor constraint; (2) remove low-carbon benefit index constraint; (3) remove pollutant reduction constraint; (4) minimize generation cost; (5) maximize generation cost.

CONCLUSION

This paper constructs a PID load regulation model to realize hybrid operation of coal power + PV power generation and optimize environmental benefits. The difference of urban environmental benefit index does not exceed 0.05, proving sensitivity. After planning, coal dependence is reduced by 13.92% while PV usage increases correspondingly. In extreme cases, the hybrid system still tends to use more coal. Future work can strengthen linkage analysis between tariff policy and generation regulation to improve trade-offs between environmental and economic benefits.

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