Research on Investment Strategy of Energy-saving Renovation of Public Buildings Driven by Carbon Trading

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Abstract. This paper investigates the investment strategy with the shortest payback period or the highest net present value based on the comprehensive income of energy conservation and carbon emission trading of different building reconstruction technologies. The analysis is conducted using a multiple regression algorithm, taking into account the price fluctuation of the initial investment and carbon emission trading. The case verification results indicate that the optimal initial investment results in a capital savings of 44.43%, a reduction in the payback period by 4.33 years, and a rise in the total investment rate by 37.92% compared to the full investment. Diverse optimal capital allocation options exist, which are subject to vary based on investment priorities between boiler replacement and rooftop PV, particularly in the context of carbon trading price fluctuations around 50 ^{3}/t. Ultimately, a venture capital decision model is developed using the probability distribution of carbon trading prices during the contract time. The model aims to optimize the overall projected return, offering owners precise and adaptable investment guidance.

Keywords: carbon emissions, public buildings, energy saving renovation, investment strategy

1. Introduction

Approximately 36% of the total energy consumption in society is attributed to buildings, whereas building carbon emissions account for around 40% of the overall carbon emissions in society.[1] The potential benefits of incorporating energy efficiency retrofit initiatives are often subject to the impact of market volatility and technological progress, leading to a notable degree of uncertainty. The occurrence of "campaign carbon reduction" can occur when different technologies are reproduced and updated without rigorous evaluation, resulting in an escalation of carbon emission intensity during the whole lifespan of the building. Therefore, the main priority for owners who want to participate in the carbon exchange is to create an ideal investment plan that can successfully traverse the ever-changing market conditions while having limited investment funds. The existing literature pertaining to the decision-making and evaluation of building retrofit schemes can be classified into three primary domains. The

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initial component pertains to the establishment of a comprehensive system for evaluating indices by assigning weight coefficients. Diakaki et al. (year) have considered multiple elements, including energy usage, carbon emissions, and expenses, and have implemented a compromise planning technique that considers the preferences of the decision maker in program development. [4] Yao Hao et al. examine the second component, which involves choosing various influencing factors for the fuzzy comprehensive evaluation scale based on the building's characteristics and climate. The primary objective of this technique is to augment the objectivity and reason inherent in the evaluation of programs. The second method entails creating a multi-objective decision-making optimization model using an optimization algorithm[2]. Song et al. provide a cost-utility optimization model aimed at mitigating carbon emissions. This model integrates several mechanisms such as subsidies, trade, and penalties. Additionally, they provide evidence for the presence of an optimal approach in mitigating emissions.[7] Conversely, Ascione et al. propose a genetic algorithm as a means to ascertain the most advantageous cost option for the complete life cycle of a structure, with a specific emphasis on energy consumption and thermal comfort.[5] In addition, Zhu Zhao et al. have devised an economic calculation model that combines energy consumption and carbon emission models with economic analysis in order to evaluate the comprehensive investment costs and benefits of the program. This approach considers the additional expenses and advantages over the whole lifespan of a building and is integrated with the concept of value engineering to identify the most beneficial retrofitting alternatives.[3] Ibn-Mohammed et al. present a robust decision support system that integrates economic and net environmental benefits in their study.[6] In order to achieve the most economical cost solution, the researchers utilize the marginal cost reduction strategy and the Pareto optimization method. T. Ibn Mohammed et al. have developed a decision support system that effectively combines economic and net environmental advantages. This system facilitates optimal decision-making by employing approaches such as marginal cost reduction and Pareto optimization. [3]

However, it is crucial for the specified study to further investigate the complex relationship between the significant benefits of the project and the costs related to various technologies and market conditions. Furthermore, it is necessary to conduct an inquiry into the prioritization of investments and the optimal approach for capital allocation, while considering the feasibility of execution. Therefore, the present study initiates by investigating the significant benefits associated with electricity conservation and carbon trading. The process involves the development of several technical models aimed at enhancing energy conservation efficiency and conducting economic analysis. This study employs a multiple regression algorithm to examine the optimal investment strategy by considering the impact of varying starting investment and carbon trading prices. Furthermore, the research integrates empirical case studies to provide decision-makers with a basis for making well-informed decisions and attaining optimal usage of resources.

2. The modeling of retrofit technologies

The present area is dedicated to the retrofitting of envelope objects, specifically windows and walls, as well as the retrofitting of lamps, optimization of air conditioning systems, rooftop photovoltaic systems, and substitution of boilers. The aim of this study is to develop performance models for energy conservation and economic analysis for each technology. The energy-efficient technologies are denoted by the variables i=1, 2, 3, 4, 5, and 6, with 1 indicating wall retrofit and 2 indicating window retrofit. The process of modeling is delineated as follows:

Equations (1) to (2) can be used to define the investment and benefits of the six energy-saving technologies stated earlier, specifically in terms of energy conservation and emission reduction.

The initial investment as follow.

$$M_i = \begin{cases} 0.1 \cdot 8.14 \cdot G_i \cdot \lambda_i, & i\text{=1,2,3,4} \\ 0.1 \cdot P_i \cdot \lambda_i', & i\text{=5,6} \end{cases} \tag{1}$$

The variables in the equation are as follows: Mi represents the initial investment of ten thousand yuan, Gi represents the energy saving of each technology, tce, κi represents the investment per unit of energy saving, yuan/kWh, ’i represents the investment per unit of power, yuan/W, Pi represents the installed capacity of photovoltaic or heat pumps, kW, and 8.14 represents the discounted power factor of standard coal, kWh/kgce.

The carbon reduction as follow.

$$C_i = \begin{cases} 0.7995 \cdot 8.14 \cdot G_i, & i\text{=1,2,3,4,5} \\ 2.0196 \cdot V_{\text{gas},i} - 0.7995 \cdot E_i, & i\text{=6} \end{cases} \tag{2}$$

The variables in the equation are as follows: Ci represents the carbon reduction of a single technology, measured in kgco2; Vgas,6 represents the boiler gas consumption, measured in m3; E6 represents the heat pump electricity consumption, measured in kWh; 0.7995 represents the electricity discount factor, measured in kg/(kWh); and 2.0196 represents the natural gas discount factor, measured in kgco2/m3.

2.1. Modifications to the enclosure

The envelope structure comprises a range of materials, including walls, roofs, doors, windows, and other components that enclose the building area. The main aim of rehabilitation is to improve the thermal insulation and airtightness of the structure through the reduction of the heat transfer coefficient. Consequently, this results in a reduction in energy dissipation within the structure. Frequent methods utilized for this objective encompass external wall insulation, multi-layer glazing, and green roofing. It is assumed that the energy-saving rate of the remodeled enclosure structure is exactly proportional to its heat transfer coefficient and area, as per the energy-saving calculation method for wall and window remodeling.

$$\xi_i = (\sigma_i - \sigma_i') \cdot A_i \cdot \omega_i, \quad i = 1,2 \tag{3}$$

$$G_i = B \cdot \xi_i, \quad i = 1,2 \tag{4}$$

Where: ξ1 , ξ2 are the energy saving rate of wall and window retrofit, %; σ, σ， are the heat transfer coefficients before and after the retrofit of wall or window, W/m2 -k; ω1 , ω2 are the energy saving rate of the retrofit of heat transfer coefficients of the unit area, and according to the engineering experience, the wall is taken to be 7.07×10-5 k/W, and the window is taken to be 3.36×10-4 k/W.[]； A1 , A2 are the total area of the wall or window, m2； G1 , G2 are the energy saving of wall and window retrofit, tce; B is the comprehensive energy consumption of building, tce; B is the comprehensive energy consumption of building, tce; B is the comprehensive energy consumption of building, tce; and B is the total energy consumption of the building, tce. wall and window retrofit energy saving.

2.2. Enhancements in Lighting Energy Efficiency

The implementation of lighting retrofits is a financially viable and remarkably efficient strategy for the energy-efficient retrofitting of public structures. Light source transformation, intelligent lighting control, and the enhancement of natural illumination are often utilized transformation strategies. Typically, these techniques result in energy savings exceeding 50%. An instance of a modest and readily attainable change is the replacement of incandescent bulbs with energy-efficient lighting. The determination of energy savings can be computationally derived by employing the below formula:

$$G_3 = (P_3 - P_3') \cdot n_3 \cdot h_3 \tag{5}$$

The variables P3 and P3Ᵽ denote the power levels before and after the retrofit of lights, measured in kilowatts. The variable n3 represents the total number of lamps and lanterns, which is one. The variable h3 indicates the length of illumination, measured in h.

2.3. Enhancements in Air-Conditioning Energy Efficiency

Air conditioning systems in large and medium-sized buildings can account for approximately 40% to 50% of the overall energy requirements. There are two viewpoints from which the enhancement of total energy efficiency in air conditioning systems can be tackled. To meet operational issues like as high flow and tiny temperature fluctuations, the transmission and distribution system can be transformed by employing pumps, fans frequency conversion, and optimizing control technologies. Furthermore, the enhancement of the cold source can be achieved by substituting high-efficiency chillers, converting the frequency of chillers, cleaning the chillers, optimizing self-control, and implementing other pertinent technologies. The aforementioned procedures are designed to address concerns pertaining to suboptimal load rates, irrational operational approaches, and little heat transfer efficiency. The calculation of energy conservation involving the repair of air-conditioning systems can be expressed as follows:

$$Q_4 = \frac{E_4}{h_4} \cdot eer \tag{6}$$

$$G_4 = Q_4 \cdot \left(\frac{1}{eer} - \frac{1}{eer'} \right) \cdot h_4 \tag{7}$$

In this context, Q4 denotes the mean cooling load during the summer season, measured in kilowatts. E4 signifies the yearly power consumption of the air conditioner, measured in kilowatts. h4 represents the annual duration of air conditioner activation, measured in hours. eer and eer) denote the overall energy efficiency of the air conditioning system prior to and following the retrofit, respectively.

2.4. Photovoltaics on rooftops

Rooftop photovoltaic prioritizes the use of clean energy, helps to cut power peak loads, often applied to user loads and business practices are relatively reliable, installation of high motivation, such as airports, stations, hospitals, schools and other scenarios, according to the "Photovoltaic Power Station Design Code" GB50797-2012, photovoltaic power generation can be calculated by the following formula:.

$$P_5 = f \cdot A_{\mathrm{roof}} \tag{8}$$

The variable P5 denotes the installed capacity of the photovoltaic (PV) system, measured in kilowatts. Aroof represents the roof area, measured in square meters. f represents the installed capacity per unit area, with a value of 0.1 kilowatts per square meter.

$$E_5 = \sum_{d=1}^{d=365} \frac{H_{A,d}}{E_{\mathrm{s}}} \cdot P_5 \cdot \eta_{\mathrm{PV}} = \sum_{d=1}^{d=365} \sum_{\tau=0}^{\tau=24} \frac{h_{A,d,\tau}}{E_{\mathrm{s}}} \cdot P_5 \cdot \eta_{\mathrm{PV}} \tag{9}$$

$$G_5 = 0.1229 \cdot E_5 \tag{10}$$

In this context, E5 represents the photovoltaic power generation, measured in kilowatt-hours (kWh). HA,d denotes the total daily irradiation intensity of the day, measured in kWh/m2. hA,d, represents the daily irradiation intensity of the day moments, measured in kWh/m2. Es represents the irradiation intensity under standard summer conditions, measured at 1 kWh/m2. βPV represents the integrated efficiency of photovoltaic power generation, assumed to be 90%[1].

The ratio of real-time consumption as follow.

$$r = \frac{E_{5,\tau}}{E_\tau} = \frac{h_{A,d,\tau} \cdot P_{\mathrm{PV}} \cdot \eta_{\mathrm{PV}}}{365 \cdot t \cdot E_s \cdot E_\tau} \tag{11}$$

In the given context, r represents the percentage of photovoltaic (PV) power consumption. E5, denotes the PV power generation at a certain instant, measured in kilowatt-hours (kWh). Eμ represents the energy consumption of the building at a particular moment, measured in kWh.

2.5. The Substitution of Electricity in Boilers

Boilers in large public buildings typically have a heating efficiency ranging from 0.8 to 0.9. In order to supply household hot water, it is common for the heating temperature to surpass 150°C or even 200°C, leading to the utilization of high-grade energy. The current level of energy usage exhibits inefficiency and poses significant environmental impact. By substituting the gas boiler with an air source heat pump, it is possible to enhance the heating efficiency to a level above 34%. This leads to a notable enhancement in energy utilization efficiency and a decrease in the likelihood of explosion during operation. Consequently, it is frequently employed for the provision of steam, boiled water, and hot water within the cafeteria and bathing facilities of the organization. The process of determining specific advantages can be expressed as follows:

The heat generation from a boiler as follow.

$$Q_{\text{boi}} = V_{\text{gas},6} \cdot q_{\text{gas}} \cdot \eta_{\text{boi}} \tag{12}$$

The heat production, denoted as Q, is measured in MJ. The low level heat production of natural gas, denoted as q, is 35.588 MJ/m3. The thermal efficiency of the gas boiler, denoted as β, is 0.9.

The capacity of air source heat pumps that have been installed.

$$P_{\text{hp}} = b \cdot A_{\text{indoor}} \tag{13}$$

The variables in the equation are as follows: P represents the power capacity of the heat pump, measured in kilowatts; a indoor represents the area of the building, measured in square meters; and b represents the heat load per unit area, as specified in the design code for heating, ventilation, and air-conditioning of civil buildings, which is 60W/m^2.

The overall energy usage of air source heat pumps as follow.

$$E_6 = \frac{Q_{\text{boi}} \cdot 0.2778}{\text{COP}} \tag{14}$$

The overall power consumption of the heat pump, denoted as E6, is measured in kilowatt-hours (kWh). The heat pump heating efficiency, as per the energy-saving design guidelines for ultra-low-energy public buildings, is denoted as COP, with a value of 4. The megajoule per kWh coefficient, kWh/MJ, is calculated to be 0.2778.

The G6 energy conservation as follow.

$$E_6 = \frac{Q_{\text{boi}} \cdot 0.2778}{\text{COP}} \tag{15}$$

The gas discount factor is 1.33 kgce/m3, while the electricity discount factor is 0.1229 kgce/kWh[11].

3. Economic assessment and investment approach

3.1. Comparison between Full and Partial Investment

In the context of realistic energy efficiency retrofit programs, consumers may have difficulties in obtaining sufficient financial resources or exhibiting a complete commitment to adopting all technological advancements. The concept of the "investment ratio coefficient xr (r=1,2,3,4,5,6)" pertains to the proportion of the total investment that is assigned to the sub-investment of the six technologies. Values ranging from 0 to 1 are assigned to the variables x1, x2, x3, x4, x5, and x6. Table 1 presents a comparative analysis of the energy efficiency and economic indicators for both the complete investment and the partial investment. The analysis assumes a linear correlation between the actual energy savings achieved by each technology and the corresponding investment.

Table.1 Comparison of energy efficiency and economic indicators on full and partial investment

	Completely committed	Real investments
aggregate capital outlay	$V_{\text{sum}} = \sum_{r=1}^{6} V_r$	$v_{\text{sum}} = \sum_{r=1}^{6} v_r$
Sub-percentage	$X_r = \frac{M_r}{M_{\text{sum}}}$	$x_r = \frac{m_r}{m_{\text{sum}}}$
The aggregate yearly energy conservation	$G_{\text{sum}} = \sum_{r=1}^{6} G_r$	$g_{\text{sum}} = \sum_{r=1}^{6} g_r \frac{m_r}{M_r}$
Annual carbon reductions in their entirety	$C_{\text{sum}} = \sum_{r=1}^{6} C_r$	$c_{\text{sum}} = \sum_{r=1}^{6} C_r \frac{m_r}{M_r}$
The aggregate yearly energy conservation	$PRO_{\text{E}} = \sigma_E \cdot \left(\sum_{r}^{5} E_r - E_6 \right)$	$pro_{\text{E}} = \sigma_E \cdot \left(\sum_{r}^{5} E_r \cdot \frac{m_r}{M_r} - E_6 \frac{m_6}{M_6} \right)$
The annual gains in carbon reduction	$PRO_{\text{C}} = \sigma_C \cdot \sum_{r}^{6} C_r$	$pro_{\text{C}} = \sigma_C \cdot \sum_{r}^{6} C_r \cdot \frac{m_r}{M_r}$
The annual gross revenues.	$PRO_{\text{sum}} = PRO_{\text{E}} + PRO_{\text{C}}$	$pro_{\text{sum}} = pro_{\text{E}} + pro_{\text{C}}$

Where: Vsum, vsum for the total full investment and the total actual investment amount, respectively, million yuan; Vr, vr for the full investment and the actual investment of each technology, respectively, million yuan; Xr, xr for the full investment and the actual investment of each technology accounted for the proportion of the total investment, (i.e., the capital allocation strategy) %; Gsum, gsum for the full investment and the actual investment of total energy savings, respectively, tce; Csum, csum for the full investment and the actual investment of annual total carbon reduction, kgco2 tce; Csum, csum are the total annual carbon reduction under full investment and actual investment, kgco2; σE is the price of electricity, Yuan/kWh; σC is the price of carbon trading, Yuan/tonne; PROE, proE are the total annual electricity saving revenue under full investment and actual investment, million yuan; PROC, proC are the total annual carbon reduction revenue under full investment and actual investment, million yuan; PROsum, prosum are the total annual carbon reduction revenue under full investment and actual investment, million yuan. PROsum, prosum are the annual comprehensive income under full investment and actual investment, respectively, RMB 10,000 yuan.

3.2. Indicators for Economic Evaluation

When performing an economic evaluation of energy-conserving renovations in pre-existing structures, it is crucial to engage in a comprehensive analysis of the initial capital outlay necessary for these renovations and the financial viability of the energy-saving technology. The examination at hand incorporates static indicators such as the rate of return on investment and the static payback period. The dynamic indicators, in contrast, include the net present value and the dynamic payback time.

Incorporating elements such as increasing energy costs and decreasing energy efficiency is necessary to include temporal value concerns. The net present value (NPV) is the aggregate net cash flow generated by a project over its whole duration, calculated by applying a predetermined discount rate to the net cash flow for each period. The determination of this calculation is based on Equation (15). In contrast, the dynamic payback period is determined by employing Equation (16) starting from the year of commissioning.

$$NPV = \sum_{t=1}^{n} NCT_{\mathrm{t}} - v_{\mathrm{sum}} = \sum_{t=1}^{n} \alpha^{t-1} \cdot pro_{\mathrm{sum}} \cdot (1+\delta)^{t} \cdot (1+\theta)^{-t} - v_{\mathrm{sum}} \tag{16}$$

$$T_{\mathrm{P,D}} = T - 1 + \frac{\left|NPV\right|_{T-1}}{(NCT)_{T}} \tag{17}$$

Let NPV represent the cumulative net cash flow over the project life cycle in millions of dollars, NCT represent the net cash flow per year in millions of dollars, a represents the energy efficiency decay rate in percentages, ı represents the energy price growth rate in percentages, represents the discount rate in percentages, TP,D represents the dynamic payback period in years, t represents the yearly fraction in years, and T represents the year in which the cumulative net cash flow of the project is positive or zero in years.

The assumption is made that the net return (NCT) of the investment project remains constant annually from the year of commissioning when the idea of time value is disregarded. The determination of the static payback period (TP,J) can be achieved by employing the subsequent equation. [ ]

$$T_{\mathrm{P,J}} = \frac{v_{\mathrm{sum}}}{NCT} \tag{18}$$

The variable TP,J represents the static payback period in years.

When disregarding the year-by-year operating and maintenance (O&M) costs, it is possible to consider the annual net return of each technology choice as equivalent to the annual profit. Additionally, the investment margin can be seen as the reciprocal of the static payback period.

$$pm = \frac{1}{T_{\mathrm{P,J}}} \tag{19}$$

Where: pm is the percentage return on investment.

3.3. Strategies for Optimal Investment

The evaluation of economic advantages connected with each technology, as well as the benefits generated from energy conservation and carbon mitigation, should be conducted comprehensively by the investment program. The determination of the ideal beginning investment amount under the current circumstances, denoted as vsum*, is achieved by creating the objective function and constraints, and employing the multivariate nonlinear regression technique. Furthermore, the most effective approach to allocate capital for different starting investments is calculated as follows: xr = (x1, x2, x3, x4, x5, x6):

(1)The objective function.

a. The minimum payback period

b. Maximum net present value for the duration of the contract

(2) Limitations

a. To maintain within acceptable limits for energy consumption per unit of floor area and per capita building energy consumption, it is imperative to establish a lower threshold for the reduction of total building energy consumption.

b. Each individual energy-saving technology has a sum of 1 for the investment ratio coefficients.

c. The investment capital required for any particular energy-saving technology must not surpass the investment capital required for the corresponding item within the comprehensive investment framework.

$$\begin{cases} g_{\text{sum}} \geq \Delta B_{\text{limit}} \\ \sum_{i=1}^{6} x_r = 1 \\ 0 \leq x_r \leq \dfrac{M_r}{v_{\text{sum}}} \end{cases} \tag{20}$$

The lower limit of the required reduction in integrated energy consumption, tce, is denoted as xi ; ^{o}Blimit.

4. Case Study

4.1. Case Presentation

(1) Concise overview of the case study

This section focuses on a case study of an arena building located in Nanjing, which serves to validate the rationality and practicality of the investment approach outlined in the preceding section. The building area of this arena is 10492.95 m2 , the roof area is 400 m2 , the wall area is 36930.55 m2 , the window area is 11152.32 m2 , the window-to-wall ratio is 0.3, and the air conditioning form is a chiller + boiler, and the total energy consumption is 196.22 tce in 2021, of which the electricity consumption is 1,269.1 thousand kWh, and the gas consumption is 30.26 kgm3 , and the energy consumption per unit of the building area is 18.7 kgce/m2 , corresponding to the limit of 16.2 kgce/m2 , converted into total energy consumption total excess 26.23 tce, details of month by month energy consumption see table 2, details of itemized energy consumption see table 3. The yearly duration of lighting is 4000 hours, with a total of 3875 lights and lanterns. Additionally, the annual opening hours for air-conditioning are 1135 hours.

Table.2 Energy consumption of the case building in 2021

Months	1	2	3	4	5	6	7	8	9	10	11	12
Electricity, kWh	9.07	8.06	7.86	7.18	11.22	12.76	14.98	16.92	13.09	10.53	7.76	7.48
Gas, km^3	5.35	3.13	2.47	1.33	1.05	0.88	0.75	0.81	1.51	2.31	4.78	5.89

Table.3 The proportion of each energy consumption of the case building in 2021

	Electricity consumption of air conditioners	Lighting consumption	Power consumption of office equipment	Uninterrupted load power consumption	boiler gas consumption
Sub-energy consumption	399,100 kWh	37.2 million kWh	256,900 kWh	241,100 kWh	30.26 km^3
Comprehensive energy consumption	49.05 tce	45.72 tce	31.57 tce	29.63 tce	40.25 tce
percentage	25 %	23 %	16 %	15 %	21 %

(2) Quantification of the advantages of retrofitting rooftop photovoltaic systems

Table 6 displays the 24-hour insolation radiation intensity for a typical day across all seasons of the year. Figure 1 illustrates the consumption of photovoltaic (PV) power generation across all seasons. It is seen that the daytime PV power output can be fully utilized due to the limited roof area. Spring is characterized by the highest rate of consumption, whereas in summer, the rate of consumption decreases from 8:00 to 16:00 due to the significant increase in electricity consumption resulting from air-conditioning load. Conversely, winter is associated with a decrease in consumption rate due to the lower intensity of insolation radiation. The aggregate yearly power production amounts to 48998.63 kilowatt-hours (kWh), accompanied by an average consumption rate of 5.75%. The details of renovation technologies for case building is shown in Table 4.

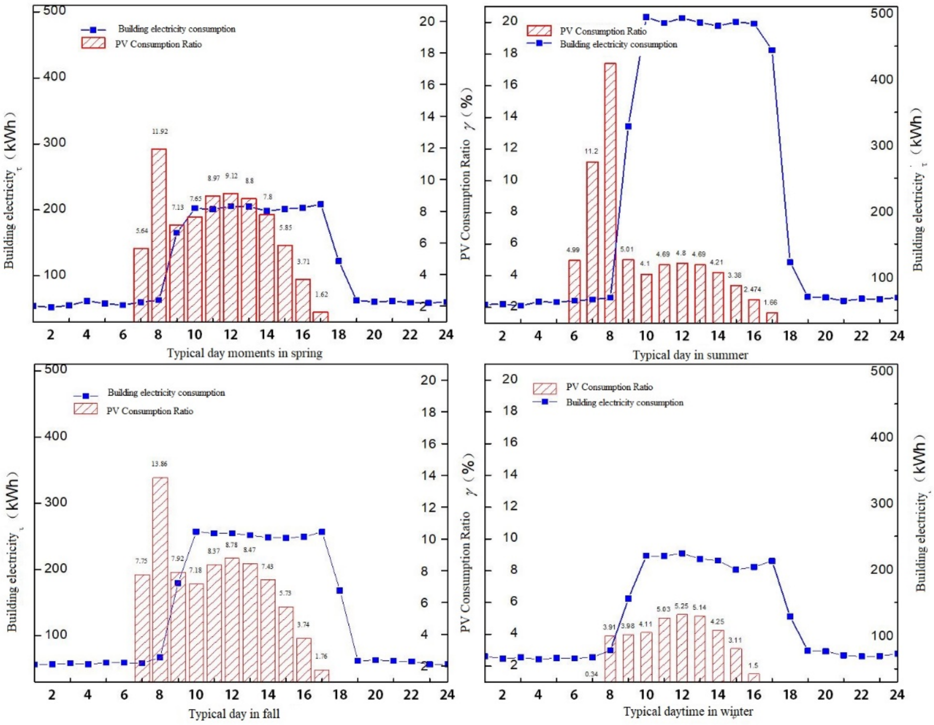

Fig. 1 Prediction of photovoltaic power generation and absorption capacity

Table.4 Details of renovation technologies for case building

Name of the structure	Parameters before modification	Retrofitting methods	Parameters after modification
wall remodeling	Heat transfer coefficient σ = 2.46 W/m^2 -k	Laying of insulation	Heat transfer coefficient σ' = 1.12 W/m^2 -k
window modification	Heat transfer coefficient σ= 5.7 W/m^2 -k	Insulated glass	Heat transfer coefficient σ' = 5.3 W/m^2 -k
Lighting retrofit	Power P_3 = 24 W	T8 Lamps for T5 Lamps	Power P_3' = 16.75 W
Air conditioning retrofit	Total energy efficiency eer = 3.39	Replacement of high-efficiency chillers + water pump frequency conversion retrofit	Total energy efficiency eer' =5.1
rooftop photovoltaic (e.g. solar)	not have	Additional rooftop PV (type)	Installed PV capacity P_5 = 40 kW
Heating equipment	Annual boiler gas consumption $V_{gas,6}$ =30260 m^3	Replacement of gas boilers with air source heat pumps	Heat pump power P_6 = 629.58 kW

Table.5 The unit-price of each energy saving technology

window modification[§]	wall remodeling[21]	Lamp Retrofit[21]	Air conditioning retrofit[21]	photovoltaic (e.g. cell)[6]	heat pumps[**]
λ_1 =15.73	λ_2 =30.18	λ_3 =5.54	$\lambda_4 = \$5.39/\mathrm{kWh}$	$\lambda'_5 = \$9/\mathrm{W}$	$\lambda'_6 = \$1.77/\mathrm{W}$

Table.6 Sunshine radiation intensity at each time of a typical day in four seasons in Nanjing

juncture	spring (time)	Xia of the Sixteen Kingdoms (407-432)	autumn	(onom.) beating a drum
6		117.00		
7	124.00	270.33	165.33	
8	275.33	438.67	341.33	111.67
9	431.33	602.67	520.00	227.67
10	567.00	741.33	675.33	332.33
11	659.33	833.67	780.33	405.67
12	685.67	866.33	817.67	431.33
13	659.33	833.67	780.33	405.67
14	567.00	741.33	675.33	332.33
15	431.33	602.67	520.00	227.67
16	275.33	438.67	341.33	111.67
17	124.00	270.33	165.33	

(3) Assessment of the energy-saving impacts and financial implications associated with six retrofit solutions.

The unit-price of each energy saving technology is shown in Table 5. The energy efficiency and investment details of the six retrofit methods under the condition of complete investment are presented in Table 7, based on the current situation of the case building. The findings indicate that the complete investment amount is 4,499,200 yuan, with each technology accounting for a share of xi = (0.3, 0.07, 0.16, 0.14, 0.25, 0.08). This implies a minimum payback period of 15.8 years and a cumulative energy saving rate of up to 39.81%.

Table.7 Energy saving benefits and investment of six renovation technologies in the case building

nicknames	Technical category	energy conservation G (tce)	Energy saving rate ξ (%)	Investment in energy savings per unit λ ($/kWh)	Initial investment M (in millions of dollars)	investment ratio Coefficient X (%)
1	Exterior wall remodeling	6.87	3.50	24.64	137.69	30.60
2	Exterior Window Modification	2.94	1.50	12.72	30.46	6.77
3	Lamp Retrofit	13.82	7.04	5.54	62.34	13.85
4	Air conditioning retrofit	16.48	8.40	5.39	72.25	16.06
5	rooftop photovoltaic (e.g. solar)	6.02	16.29	7.35	36.00	24.71
6	Boiler Retrofit	31.97	3.07	4.27	111.19	8.00
add up the total		78.11	39.81		449.92	100

Note: According to the actual energy price market conditions in Nanjing, the electricity price is taken as 0.5 yuan/kWh, and the natural gas price is taken as 3.8 yuan/m3 . On July 16, 2022, China's carbon emissions trading was officially launched in the Shanghai Environment and Energy Exchange, with the opening price of carbon quota at 49 yuan/tonne, and the price of the first national carbon transaction at 52.78 yuan/tonne. As the carbon trading in the field of construction has not yet been opened, with reference to the first opening price, this paper tentatively sets the construction carbon trading price at RMB 50/tonne (range of change: RMB 20-90/tonne). Since the dynamic economic indicators need to consider the value of time, the case study takes the energy efficiency decay rate $\alpha = 3\%$, energy price growth rate $\delta = 7\%$; discount rate $\Theta = 6\%$[16] .

4.2 Results and Discussion

This section delves into the exploration of various aspects related to investing in energy efficiency retrofits for existing public buildings. Specifically, it examines the optimal investment amount to maximize the net present value over the contract period, the adjustment of investment ratio coefficients for each technology to minimize the payback period, and the strategies for managing fluctuating carbon trading prices.

(1) The impact of physical investment levels on the most effective technique for allocating capital

According to Figure 2, there is a modification in the optimal investment plan that aligns with the lowest payback period, considering the initial investment at the carbon trading price of $50 per ton. According to the data presented in Figure 2, it can be observed that as the original investment amount drops, the investment proportion coefficients for external wall, exterior window rehabilitation, and boiler replacement reduce to zero. The investment fraction of boiler replacement exhibits an initial increase followed by a subsequent decline, indicating a marginal improvement in its economic viability compared to the preceding two options. The investment share for air conditioning and light fixture retrofitting gradually increases as the initial investment decreases, resulting in a larger return on investment. Due to its more inferior economic performance compared to lamps and air conditioners, rooftop photovoltaic exhibits a pattern of initial growth followed by subsequent decline. In conclusion, the recommended order of investment for the six retrofit technologies is as follows: air conditioning retrofit, followed by lighting retrofit, rooftop solar, boiler replacement, window retrofit, and façade retrofit.

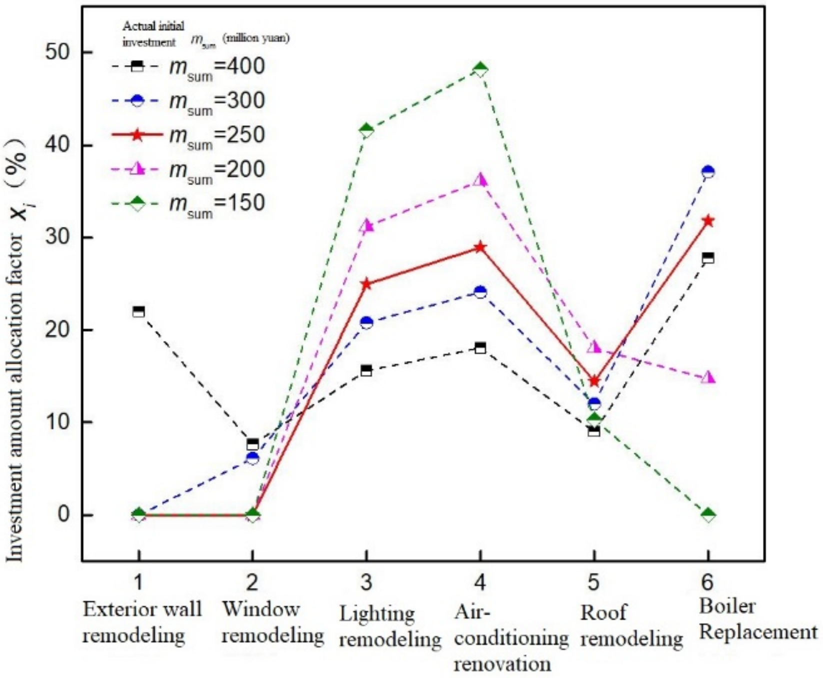

Fig. 2 The effect of actual investment amount on optimal capital allocation strategy

(2) The Influence of the Actual Investment Amount on the Minimum Payback Period and Net Present Value

Figure 3 illustrates the relationship between the payback period and net present value (NPV) as a function of the initial investment amount, within the context of the optimal investment plan at the carbon correct price of $50 per ton. As the initial investment rises, there is a gradual increase followed by a significant increase in the shortest payback period. This can be attributed to the fact that as the initial expenditure increases, a greater proportion of funds is directed towards the less economically viable retrofit technology, leading to an extended payback period. In contrast, while considering the 18-year contract time as an illustrative case, it can be observed that as the initial investment rises, the net present value (NPV) initially exhibits a gradual increase followed by a rapid decline, ultimately reaching its peak value of 2.5 million dollars. In conjunction with Figure 2, it is evident that when the investment amount falls below 2.5 million yuan, the payback period is diminished as a result of the heightened allocation of funds towards lighting retrofit and air-conditioning retrofit. However, this also engenders a decline in the annual net cash flow, consequently resulting in a decrease in the net present value (NPV) over the duration of the contract. It is evident that in order to optimize the net present value (NPV) during the duration of the contract, an investment level of $2.5 million is deemed best. This decision is based on a static payback period of 11.47 years and a cumulative NPV of $858,300.

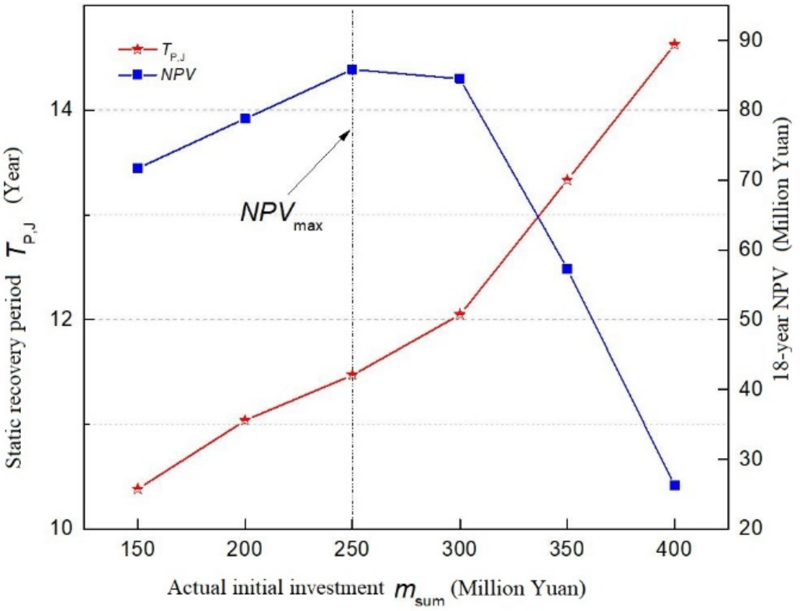

Fig. 3 The effect of actual investment amount on the minimum payback period and net present value

(3) The influence of carbon trading prices on the minimal payback period, capital allocation strategy, and net present value.

Once the ideal initial investment amount has been determined, it is often necessary to dynamically alter the investment strategy in response to fluctuations in the carbon trading price. This adjustment involves allocating the investment amount in a reasonable manner to each retrofit technology. According to the data presented in Figure 4, there is a positive correlation between the carbon trading price and the annual net cash flow. This relationship results in a gradual reduction in the minimum payback period and an overall increase in the net present value throughout the duration of the contract. The duration of the dynamic payback period is marginally greater than that of the static payback period as a result of the incorporation of the concept of time value. The ideal allocation strategy for carbon trading at a price of \$50/ton is xi = (0, 0, 0.25, 0.29, 0.02, 0.44). For every \$10/ton rise in the carbon trading price, the net present value (NPV) increases by \$30,900. At a carbon trading price of \$50 or more, the most advantageous allocation method can be represented by the equation xi = (0, 0, 0.25, 0.29, 0.14, 0.32). This strategy results in an increase of \$35,600,000 in the net present value (NPV) for each \$10/ton rise in the carbon trading price.

(4) This study examines the influence of initial investment and carbon trading price on investment returns.

According to Figure 5, when the carbon trading price remains constant, the total return on investment increases by 37.92% when the optimal investment amount is used. This is primarily because the envelope renovation consumes a significant portion of the investment amount, resulting in a failure to fully utilize the investment due to the poor economy. When the carbon trading price increases from \$20/tonne to \$50/tonne, the total return on investment increases by 2.97%. However, the share of boiler substitution decreases, while the share of all other technological subcomponents increases. This phenomenon can be attributed to the fact that the replacement of boilers leads to an increase in electricity consumption, while simultaneously reducing gas consumption. The disparity in carbon reduction between the two options is the determining factor. In this particular scenario, the carbon reduction achieved through boiler substitution is merely 6.03% compared to rooftop PV, given an equivalent investment amount. This indicates that the former is less susceptible to the volatility of carbon trading prices in comparison to the latter. At a carbon trading price of \$50/ton, the yearly investment return of boiler substitution is higher than that of rooftop PV. Conversely, at a carbon trading price of \$50/ton, the converse holds true, resulting in a preference for allocating a greater investment amount towards boiler substitution.

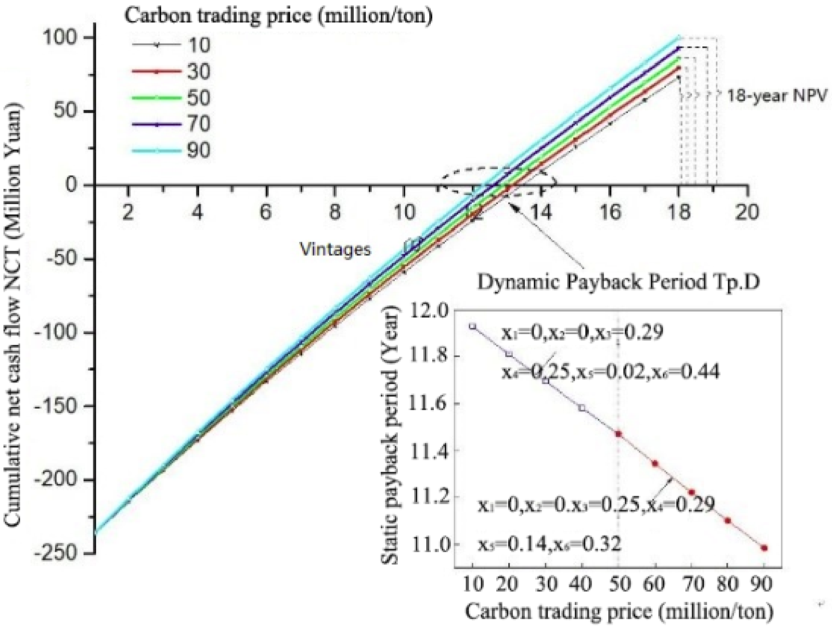

Fig. 4 The effect of carbon trading price on minimum payback period, capital allocation strategy and net

present value

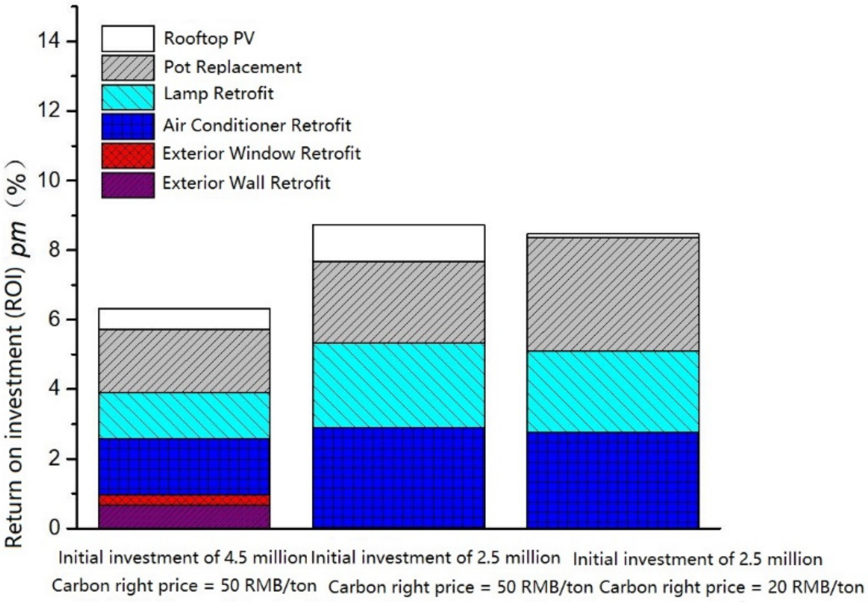

Fig. 5 The impact of initial investment and carbon price on return investment ratio

(5) Investment models for energy efficiency retrofit projects that consider the volatility of carbon trading prices and their associated risks.

Based on the above study, it is evident that alterations in carbon trading prices have an impact on the best capital allocation approach across various investment magnitudes. During the initial investment phase of the project, it is important to take into account the volatility of the carbon trading price over the contract period. Therefore, it is crucial to consider the value of time, quantify the effects of uncertainties, and apply the risk investment theory. This will help determine the best initial investment and capital allocation strategy based on the total expected returns of various investment options. This approach serves as a foundation for making long-term and multi-stage investment decisions. The specific methods to be employed are as follows:

The first step involves determining the carbon trading price natural event C,j (where j ranges from 1 to n) in year t, which corresponds to the probability of occurrence pj (C,j(t)). Geometric Brownian motion, artificial neural network modeling, and other methodologies can be utilized to solve the likelihood of carbon trading prices.

Step 2: Utilizing the findings from Section 2.3, determine the most advantageous approach to allocate capital for the initial investment vsum,i in year t, given the carbon trading price C,j: (x1, x2, x3, x4, x5,x)6ij’, (j'=jT). Construct a decision matrix (Eq. 21) to calculate the expected return qij’(t) for year t, which subsequently leads to the total expected return NPVij’ over the contract period of the initial investment vsum,i.

Under the condition of an initial investment vsum,i (year t), the choice matrix is as follows:

$$\begin{array}{cc} & \begin{array}{cccc} \sigma_{C,1} & \sigma_{C,2} & \cdots & \sigma_{C,n} \\ p_1\left(\sigma_{C,1}\right)^{(t)} & p_2\left(\sigma_{C,2}\right)^{(t)} & \cdots & p\left(\sigma_{C,n}\right)^{(t)} \end{array} \\ \begin{array}{c} \left(x_1,x_2,x_3,x_4,x_5,x_6\right)_{i1} \\ \left(x_1,x_2,x_3,x_4,x_5,x_6\right)_{i2} \\ \vdots \\ \left(x_1,x_2,x_3,x_4,x_5,x_6\right)_{in} \end{array} & \begin{bmatrix} NCT_{11}^{(t)} & NCT_{12}^{(t)} & \cdots & NCT_{1n}^{(t)} \\ NCT_{21}^{(t)} & NCT_{22}^{(t)} & \cdots & NCT_{2n}^{(t)} \\ \vdots & \vdots & \vdots & \vdots \\ NCT_{n1}^{(t)} & NCT_{n2}^{(t)} & \cdots & NCT_{nn}^{(t)} \end{bmatrix} \end{array} \tag{21}$$

Anticipated yield in year t::

$$q_{ij'}^{(t)} = \sum_{j=1}^{n} NCT_{jj'}^{(t)} \times p_j\left(\sigma_{C,j}\right)^{(t)} \tag{22}$$

The variables qij'(t) and NCTij(t) represent the anticipated return and net cash flow in year t of the initial investment program vsum,i, respectively, measured in million dollars.

The total expected return over the contract time (t=1 to k) is equal to the initial investment vsum,i.

$$NPV_{ij'} = \sum_{t=1}^{k} q_{ij'}^{(t)} - v_{\text{sum},i} \tag{23}$$

The variable NPVij' represents the anticipated total return generated by the initial investment program vsum,i during the specified contract time, measured in ten thousand yuan.

To maximize the total expected return over the contract time, it is necessary to satisfy the optimal capital allocation strategy corresponding to sum,i (x1, x2, x3, x4, x5,x)6ij'*.

$$NPV_{ij'*} = \max_{1\le j'\le n} NPV_{ij'} \tag{24}$$

In order to determine the highest total expected return over the contract time for each of the m initial investment possibilities vsum,i (where i ranges from 1 to m), it is necessary to repeat step 2. Additionally, the optimal initial investment amount vsum,i* must be satisfied.

$$NPV_{i*j'*} = \max_{1\le i\le m} NPV_{ij'*} \tag{25}$$

In conclusion, the most advantageous approach for managing risky investments in the context of volatile carbon trading prices can be expressed as follows: the initial investment amount, denoted as vsum,i*, and the capital allocation strategy, represented by (x1, x2, x3, x4, x5, xx)6i*j'*.

5. Conclusion

This study aims to enhance the emission reduction strategy of public institutions through the implementation of a carbon trading mechanism. Additionally, it seeks to enhance the decision-making capabilities and investment returns of owners by conducting an energy efficiency and economic analysis of commonly used energy-saving retrofit technologies for existing public buildings. The study also employs multiple regression algorithms to determine the optimal investment strategy, considering the dynamic nature of initial investment and carbon trading prices. The findings derived from the case study are as follows:

(1) The complete investment necessitates a sum of \$4,499,200, accompanied by a minimum static payback period of 15.8 years. This aligns with an ideal investment strategy denoted as xr = (0.3, 0.07, 0.16, 0.14, 0.25, 0.08), and a cumulative energy saving rate of up to 39.81%.

(2)According to the analysis, the most advantageous investment amount for the project within the specified timeframe is \$2.5 million. This investment yields a net present value of \$858,300 and a minimum static payback period of 11.47 years. At a carbon price of \$50 per ton, the optimal investment amount yields a total return on investment that is 37.92% higher than the full investment.

(3) At an optimal investment amount of \$50/ton, the allocation strategy that maximizes the shortest static payback period is as follows: xr = (0, 0, 0.25, 0.29, 0.02, 0.44). For every \$10/ton rise in the carbon trading price, the NPV improves by \$30,900. The allocation method associated with the shortest payback period, given a carbon trading price of \$50 or less, is represented by the equation xr = (0, 0, 0.25, 0.29, 0.14, 0.32). This strategy results in a net present value (NPV) increase of \$35,600,000 for each \$10 increment in the carbon trading price.

(4) Boiler substitution technology exhibits a lower susceptibility to carbon trading price variations compared to rooftop photovoltaic. At the same investment amount, its carbon reduction is only 6.03% of that of rooftop photovoltaic. When the carbon trading price is less than 50 yuan per ton, the yearly return on investment for boiler replacement is higher than that of roof photovoltaic. Conversely, when the carbon trading price is less than 50 yuan per ton, the return on investment is lower.

(5) In situations where the carbon trading price exhibits volatility, it is advisable to formulate an optimal risk investment strategy using an optimization algorithm. This algorithm should be based on the objective probability of price and the criterion of greatest expected value.

The findings of this study can provide valuable insights for public building owners in formulating effective investment and capital allocation strategies for energy-efficient retrofits. This is particularly relevant when confronted with the simultaneous implementation of multiple retrofit projects and fluctuating carbon market prices. By utilizing these insights, owners can accurately strategize emission reduction pathways and allocate limited funds in a rational manner.

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