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Cost-benefit analysis on green building energy efficiency technology application: A case in China

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ABSTRACT

In order to initiate economic evaluation of green buildings and foster their development, this article conducts the cost–benefit evaluation of energy efficiency technology application (EETA) on green buildings in China. Based on the economic evaluation theory of construction project (EETCP), the authors first establishes the theoretical framework system of cost–benefit evaluation of the EETA on green buildings and then develops the analysis methods of incremental costs and quantitative calculation formula of incremental benefits of the EETA on green buildings. Using these theories and methods, this article takes the Wanke City project in China as a study case, conducts the cost–benefit empirical analysis of the EETA on green buildings, and draws the following important conclusions: (1) the incremental costs of the EETA account for a large proportion of total incremental costs of green buildings, which are more than 50% in this case; (2) the EETA on green buildings can bring incremental economic benefits, as well as environmental benefits; (3) if only consider the incremental economic benefits of the EETA on green buildings, the financial evaluation indexes show green buildings do not have market investment potential; (4) among all the factors influencing the financial evaluation results of the EETA on green buildings, power price is the most sensitive factor, followed by the unit incremental costs, and the lifetime has the smallest influence.

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1. Introduction

Developing green buildings is an important strategic way to realize sustainable development, save resource and energy, and protect environment. In order to promote the healthy development of green buildings, many countries issue green buildings evaluation standard, such as BREEAM of the UK, CASBEE of Japan, GBTool of Multinational Cooperation and LEED of the USA, which all aim to evaluate the "environment performance grade" of green buildings [1–3]. In 2006, China issued "Evaluation Standard for Green Building (ESGB)", which is the first multi-objective and multi-level comprehensive evaluation standard of green building "environment performance grade" in China [4]. In 2008, China began to implement the green building evaluation label system. There are 10, 20, 82 new buildings acquiring green building evaluation labels in 2008, 2009 and 2010, respectively [5]. By the end of 2012, there are total 742 new buildings acquiring green building evaluation labels in China, and total building areas had reached 75.43 million m^2 [6]. This shows that the development of green buildings have kept rapid momentum in China. However, compared by the new building areas of nearly 2 billion m^2 each year, the development scale of green buildings is still very small in China.

Analyzing the international existing green building evaluation systems, it can be found that these evaluation systems do not involve the economic evaluation of green buildings. For instance, BREEAM, LEED, CASBEE and ESGB do not contain such economic evaluation. Although the GBTool system, as an evaluation framework, proposes to evaluate cost benefits, it does not provide specific evaluation contents and methods. Currently, many people's awareness about green buildings is not enough comprehensive and accurate, they think that green buildings require high investment and high cost, and do not want to develop or purchase green buildings, which hinders the development of green buildings in China. Hence, it is very necessary to construct the theoretical method system of green building cost–benefit analysis from a technical and economic point of view, which has important theoretical value and practical significance for the healthy development of green buildings.

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Table 1
Level of green standard and average green cost premium.

Level of green standard	Average green cost premium (%)
Level 1—Certified	0.66
Level 2—Silver	2.11
Level 3—Gold	1.82
Level 4-—Platinum	6.50
Average of 33 buildings	1.84

Table 2
Financial benefits of green buildings summary of findings (per ft^2).

Item	Category	20-year *NPV*
1	Energy value	$5.79
2	Emissions value	$1.18
3	Water value	$0.51
4	Waste value(construction only)-1 year	$0.03
5	Commissioning O&M value	$8.47
6	Productivity and health value (certified and silver)	$36.89
7	Productivity and health value (gold and platinum)	$55.33
8	Less green cost Premium	$4.00
9	Total 20-year *NPV* (certified and silver)	$48.87
10	Total 20-year *NPV* (gold and platinum)	$67.31

2. Literatures review

At present, many scholars at home and abroad are focusing on the research about economic performance resulted by green buildings, which mainly covers the following three aspects:

(1) Analysis on economic, environmental and social benefits generated by the green building technology application [7–11]. For instance, Nalewaik and Venters [7] think green buildings can bring tangible and intangible benefits; besides, with the increase of resources and energy's price, cost saving of resources and energy will make green buildings generate significant economic benefits. Ries et al. [8] takes new green plant as a case, and analyzes quantitatively economic and environmental benefits brought by the green plant, which mainly includes increasing working efficiency and human health, decreasing energy consumption, operating and maintenance costs; Specifically, the case study shows that working efficiency is increased by 25%, and energy is saved by 25%. Kats [9] thinks that the benefits brought by green buildings include saving energy and water, decreasing waste discharge, increasing indoor environment quality, employee's satisfaction and work efficiency, as well as decreasing health costs, equipment operation costs and maintenance costs.

(2) Study on incremental costs of green buildings technology application [9,12–18]. Through comparative study on the costs of 33 green buildings and conventional buildings of the same type, Kats [9] finds that the average incremental cost is only $3–5 per square foot, and the average cost increasing rate is only 1.84%, which is shown in Table 1.

By collecting the construction cost data of 221 buildings (including teaching buildings, laboratories, libraries, community centers and so on) and comparing the unit construction cost, Morris [13] finds that the difference of construction cost is very big even among the same type of buildings, which mainly depends on the type of property, no matter whether the green buildings get the LEED certification or not. Zhang et al. [14] examines the costs and barriers in applying the green elements to the process of developing property projects, they find that the passive design strategies are comparatively inexpensive to apply as opposed to the active design strategies and the major barriers, the higher costs have hindered the extensive application of green technologies in China. By statistically analyzing the incremental costs of 18 projects participating the green building certification label (9 public green buildings, 9 residential green buildings), Sun et al. [15] find that the major factors influencing on the incremental costs are: renewable energy application (48.20%), saving energy of envelope structure (23.20%), building intelligent (16.10%), indoor environment control (7.5%), water utilization and rainwater collection (2.60%). Chen [16] applies two indexes of "unit area incremental cost" and "incremental cost ratio" to analyze the incremental costs of green buildings, and gets that unit area incremental cost is 6.01$/m^2 for one-star green building label, 16.28$/m^2 for two-star green building label and 35.48$/m^2 for three-star green building label, and that unit area incremental cost ratio is 1.0% for one-star green building label, 2.2% for two-star green building label and 3.4% for three-star green building label.

(3) The cost–benefit evaluation of green building technology application [8,9,19–24]. Ries et al. [8] conducts a financial evaluation on the new green plant project utilizing three financial indexes of the net present value (*NPV*), breakeven period and B/C, which shows that investing new green plant is a correct decision from financial benefits aspect. Kats [9] analyzes on the present value of incremental benefits and costs of 33 green buildings obtaining the LEED certification in 20 years of study period, which indicates that total financial benefits of green buildings are over ten times the average initial investment required to design and construct a green building, and energy savings alone exceed the average incremental costs associated with building green, and building green is cost-effective and make financial sense (see Table 2). Li and Tian [19] constructs an incremental cost–benefit model of green buildings in the whole life cycle, proposes that the comprehensive benefits of green buildings in the whole life cycle can be reflected by two indexes, one is the *NPV* of comprehensive benefits, the other is the incremental cost–benefit ratio, and through case analysis, she draws a conclusion that green buildings have economic feasibility.

In brief, the literatures above-mentioned mainly study on economic, environmental and social benefits of green buildings, and cost–benefit evaluation of green technology application on green public buildings and green plant buildings from the view of qualitative and quantitative point. However, there are a few of articles on the cost–benefit evaluation of green technology application on large-scale residential area in China. In this paper, taking the large-scale green residential area in China as a study case, the authors would systematically carry out the cost–benefit analysis on energy efficiency technology application (EETA) on green buildings.

3. Analysis methodologies

3.1. Evaluation method

According to the EETA on proposed green construction project, green building energy efficiency scheme (GBEES) will first be set up; then this project's virtual baseline building energy efficiency scheme (BBEES) which can meet both the national and local compulsory energy efficiency standards will also be set up; finally, based on the GBEES and BBEES, economic evaluation theory of construction project (EETCP) would be applied to analyze the cost–benefit of the EETA on green buildings [25]. The basic flow of cost–benefit analysis on the EETA of green buildings is shown in Fig. 1.

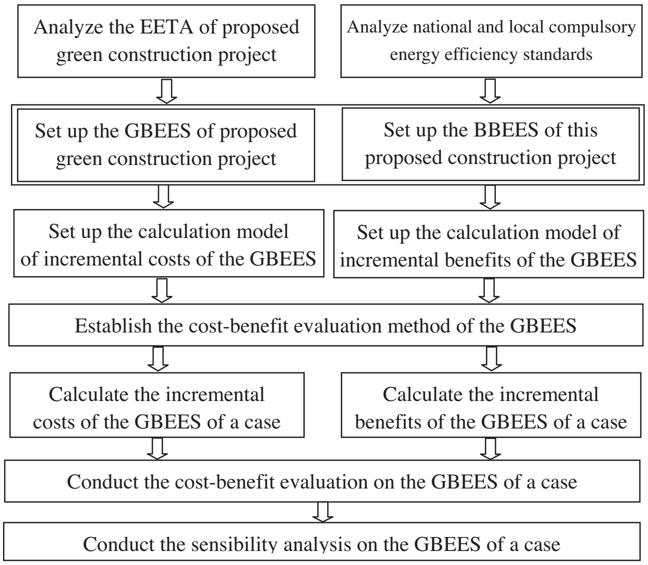

Fig. 1. The basic flow of cost–benefit analysis of the EETA on green buildings.

3.2. Evaluation index

In this article, the GBEES and the BBEES are considered as two mutually exclusive type schemes. The payback period and the internal rate of return of incremental investment are selected as the evaluation indexes for economic evaluation on the two schemes.

3.2.1. Payback period of the incremental investment

The payback period of the incremental investment (ΔP_t) refers to the number of years required to compensate for the incremental costs with the incremental benefits when the GBEES is adopted, and the formula is:

$$\sum_{t=0}^{\Delta P_t} [(CI_{GB} - CI_{BB})_t - (CO_{GB} - CO_{BB})_t] = 0 \tag{1}$$

where $(CI_{GB} - CI_{BB})$ represents the incremental benefits of the GBEES subtracts that of the BBEES in the t year; $(CO_{GB} - CO_{BB})_t$ represents the incremental costs of the GBEES subtracts that of the BBEES in the t year.

Then, the calculated ΔP_t is compared with the basic investment payback period (P_c): if $\Delta P_t \leq P_c$, the incremental costs of the GBEES can be recovered within the specified time, and the conclusion of cost–benefit evaluation on the GBEES can be accepted; if $\Delta P_t > P_c$, the incremental costs of the GBEES cannot be recovered within the specified time, and the conclusion of cost–benefit evaluation of the GBEES cannot be accepted.

3.2.2. Internal rate of return of the incremental investment

The internal rate of return of the incremental investment (ΔIRR) refers to the discount rate at which the accumulated *NPV* of the incremental benefits equals to the accumulated *NPV* of the incremental costs between the GBEES and the BBEES during the project calculation period of N, and the formula is:

$$\Delta NPV\,(\Delta IRR) = \sum_{t=0}^{N} [(CI_{GB} - CI_{BB})_t - (CO_{GB} - CO_{BB})_t] \times (1 + \Delta IRR)^{-t} = 0 \tag{2}$$

Then, the calculated ΔIRR is compared with the basic rate of return (i_c): if $\Delta IRR \geq i_c$, the conclusion of cost–benefit evaluation of the GBEES can be accepted; if $\Delta IRR < i_c$, the conclusion of cost–benefit evaluation of the GBEES cannot be accepted.

4. Analysis on the incremental costs of the GBEES

4.1. The EETA on green buildings

The EETA on green buildings mainly involve the EETA on building envelope structure, improving energy utilization efficiency, renewable energy utilization and green lighting. The EETA on building envelope structure not only includes lowering the heat transfer coefficient of external walls, roof, ground, windows and doors, but also reducing the air permeability of doors and windows. Improving energy utilization efficiency refers to the improvement of energy conversion efficiency, pipe networks transfer efficiency and energy-using efficiency of terminal equipments, as well as the adoption of cooling heating power technology. The renewable energy utilization in the green buildings mainly includes the application of solar energy light heat system technology, solar energy light electricity system technology, ground source heat pump technology, and use of wind energy and biological energy and so on.

4.2. The incremental costs calculation of the GBEES

4.2.1. The basic conception of incremental costs

The incremental costs of the GBEES refers to all incremental costs directly measured by currency in the construction period due to proposed buildings adopting green energy efficiency technologies rather than baseline energy efficiency technologies which is required compulsorily by the national and local policies [4]. For example, new buildings in Beijing are required to meet the design standard to perform 65% energy efficiency, which can be regarded as the compulsory requirements in Beijing; so, in this case, all incremental costs directly measured by currency and caused by adopting green energy efficiency techniques rather than 65% energy efficiency techniques in the construction period are all the incremental costs of the GBEES.

4.2.2. The basic principles of incremental costs calculation

China includes five climate zones: severe cold zone, cold zone, hot summer and cold winter zone, hot summer and warm winter zone and temperate zone, which can be seen in Fig. 2. Due to different natural ecological conditions, buildings energy efficiency standards and development levels, green energy efficiency standards and contents in different climatic zones are not the same, which leads to different basis and methods for calculating the incremental costs of the GBEES. At present, the methods for calculating the incremental costs of the GBEES in different places of China are very different, which results in the incremental costs of the GBEES huge difference. For example, one project's incremental costs of green technologies application in Shanghai are 55.72$/m^2, while the incremental costs of another project's green technologies application in Hangzhou are 311.88$/m^2, which are 5.6 times as great as that in Shanghai [15]. Both projects are declared as three-star green buildings, and locate in the identical climate zone, but the difference of incremental costs is so big, which indicates it is very necessary to construct reasonable basic principles and methods for calculating the incremental costs of the GBEES.

4.2.2.1. Determine the calculation range of the incremental costs. According to the ESGB, evaluation index system of green building consists of land saving and outdoor environment, energy saving and utilization, water saving and utilization, material saving and utilization, indoor environmental quality, operation and maintenance. Therefore, the incremental costs caused by the EETA on green buildings, which belongs to the scope of evaluation index

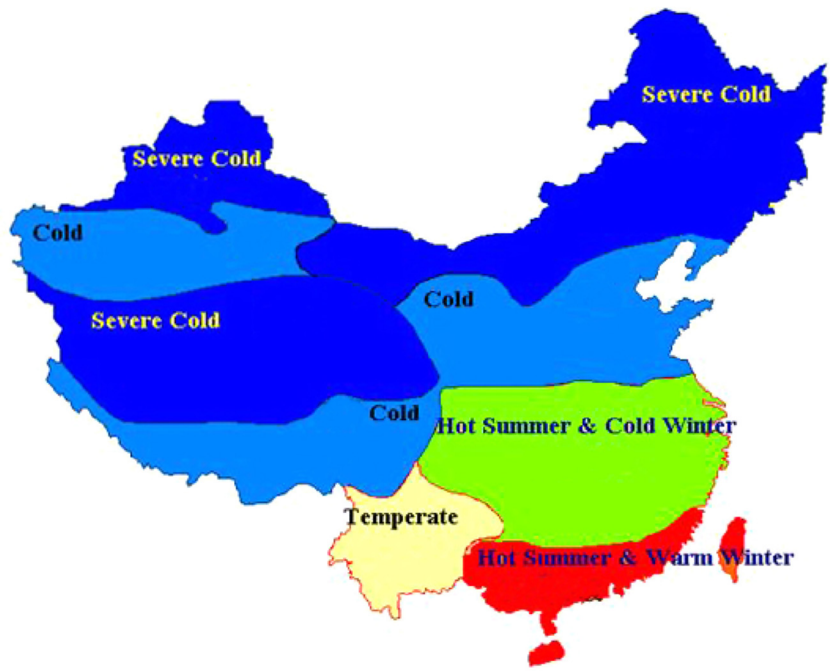

Fig. 2. Building thermo-technical design partition picture in China.

system of energy saving and utilization, should be considered as the incremental costs of the GBEES; otherwise, the costs should not be considered as the incremental costs of the GBEES.

4.2.2.2. Determine the starting point of incremental costs-BBEES. The starting point of incremental costs-BBEES is the basic reference point of calculating incremental costs, which directly influences the final calculation result of incremental costs. BBEES refers to the energy efficiency scheme with the same building type, the same building function and the same scale, which meets both the national and local compulsory energy efficiency standards. The incremental costs refer to the costs of the GBEES relative to the BBEES. At present, most of areas in China have performed the compulsory standard of 50% energy efficiency, while Beijing, Shanghai, Tianjin, and Chongqing have been the first cities to perform the compulsory standard of 65% energy efficiency. Therefore, the BBEES which is applied to calculate incremental costs of the GBEES should be different in the five climate areas in China.

4.2.2.3. Adopt the "with and without methods" to calculate the incremental costs. Calculating incremental costs of the GBEES should adopt the "with and without methods". "With" refers to the costs caused by EETA in the GBEES; "without" refers to the costs caused by EETA in the BBEES. The incremental costs of the EETA on green buildings should be the differential costs between the "with" and the "without".

4.3. The basic methods of calculating incremental costs

Due to the different construction phase, design depth and related data of proposed green buildings, incremental costs calculation of the EETA on the GBEES can adopt the different methods as below.

4.3.1. The investment index estimation method

During the decision-making stage of construction project, when the star level and construction scale of green buildings are settled, meanwhile the specific construction design scheme and contents are not available, the incremental costs of the GBEES of proposed green buildings can be calculated based on the investment index estimation method. The formula is as follows [26]:

$$\Delta C_{PB} = A \times \Delta P_{CB} \times k \tag{3}$$

where ΔC_{PB} represents the incremental costs of the GBEES of proposed green buildings; A represents the architecture areas of proposed green buildings; ΔP_{CB} represents the incremental investment index of unit area which can be obtained by the completed green buildings with the same type, the same star level and located in the same climate area; k represents the comprehensive adjustment coefficient of changes in the quota, price, and expenses due to the time factor.

4.3.2. The unit production capacity estimation method

During the decision-making stage of construction project, when the star level and construction scale of green buildings are settled, while the specific construction design scheme and contents are not available, and local government administrative department does not issue the incremental investment estimated indexes, the incremental costs of the GBEES of proposed green buildings can be calculated based on the unit production capacity estimation method [26]. The formula is as follows:

$$\Delta C_{PB} = \left(\frac{\Delta C_{CB}}{A_{CB}}\right) \times A_{PB} \times k \tag{4}$$

where ΔC_{PB} represents the incremental costs of the GBEES of proposed green buildings; ΔC_{CB} represents the incremental costs which can be obtained by the completed green buildings with the same type, the same star level and located in the same climate area; A_{PB} represents the architecture areas of the completed green buildings; A_{PB} represents the architecture areas of proposed green buildings.

4.3.3. The bill of quantity estimation method

During the design-making stage of construction project, if preliminary design drawings or more specific construction design drawings have been provided, the main contents of the GBEES of proposed buildings should be basically confirmed, then the bill of quantity (BOQ) of the GBEES can be formed, meanwhile the BOQ of the BBEES of proposed buildings can also be formed. So, according to the differences of the BOQ between the GBEES and the BBEES of proposed buildings, the incremental costs of the GBEES can be calculated with the BOQ estimation method, the specific formula is as follows:

$$\Delta C_{PB} = \sum_{i=1}^{n} Q_i^{GB} \times P_i^{GB} - \sum_{j=1}^{m} Q_j^{BB} \times P_j^{BB} \tag{5}$$

where Q_i^{GB} represents the engineering quantities of the ith EETA on the GBEES; P_i^{GB} represents the unit comprehensive costs of the ith EETA on the GBEES; Q_j^{BB} represents the engineering quantities of the jth EETA on the BBEES; P_j^{BB} represents the unit comprehensive costs of the jth EETA on the BBEES.

5. Analysis on the incremental benefits of the GBEES

5.1. The concept of incremental benefits

The incremental benefits of the GBEES refer to the incremental benefits brought by energy saving (power saving, coal saving, gas saving and so on) and reduction of pollutants emission (such as CO_2, SO_2, NO_x and so on) during the whole life cycle due to adopting the GBEES relative to the BBEES of proposed buildings. The incremental benefits (ΔB) of the GBEES mainly include incremental economic benefits (ΔB_E) and incremental environmental benefits (ΔB_H), which can be expressed by the following formula:

$$\Delta B = \Delta B_E + \Delta B_H \tag{6}$$

5.2. Analysis on incremental economic benefits of the GBEES

5.2.1. Calculation on incremental effects of the EETA of envelopes structure

The influence of green buildings' envelopes structure on building energy consumption mainly embodies in two aspects: thermal insulation in winter and cold insulation in summer. Therefore, the calculation on the incremental effects of the EETA on green buildings' envelopes structure should consider two aspects: coal saving effects in winter and air-condition power saving effects in summer.

5.2.1.1. Calculation on coal saving effects in winter. Assume that the index of heat loss (IHL) of the BBEES is HI_1, the IHL of the GBEES is HI_2, the architecture areas of green buildings are A, the annual average efficiency of heat source and heat pipe networks is Eff, the days of heating are Z, the heat value of standard coal combustion is H, according to related design standard [27], then, the amounts of energy conservation ΔE_W and coal conservation ΔQ_M^W of green buildings' envelopes structure during the winter heating period can be calculated as follows:

$$\Delta E_W = \Delta E_W(\Delta HI, A, Eff, Z) = \frac{(HI_1 - HI_2) \times A \times Z}{Eff} \tag{7}$$

$$\Delta Q_M^W = \frac{\Delta E_W(\Delta HI, A, Eff, Z)}{H} = \frac{(HI_1 - HI_2) \times A \times Z}{Eff \times H} \tag{8}$$

5.2.1.2. Calculation on air-condition power saving effects in summer. Assume that the index of cool loss of the ith room of green buildings in summer is q_i, the architecture areas of the ith room are A_i, the days of using air-conditioning of the ith room in summer are D_i, the average hours of using air-conditioning of the ith room every day are h_i, then, total amounts of cool loss of green buildings in every summer can be calculated as follows:

$$Q_C = \sum q_i \times A_i \times h_i \times D_i \tag{9}$$

Assume that energy efficiency ratio of air-conditioning cooling is the COP, total power consumption amounts of air-conditioning cooling of green buildings in summer can be calculated as follows:

$$Q_{EG} = \frac{Q_C}{COP} = \frac{\sum q_i \times A_i \times h_i \times D_i}{COP} \tag{10}$$

Assume that energy efficiency rate of the GBEES is a_1, power consumption amounts of air-conditioning cooling of the GBEES in summer are Q_{EG}; while energy efficiency rate of the BBEES is a_2, power consumption amounts of air-conditioning cooling of the BBEES in summer are Q_{EB}. Therefore, power conservation amounts of air-conditioning cooling of the GBEES relative to the BBEES in every summer can be calculated as follows:

$$\begin{aligned}\Delta Q_1^E &= Q_{EB} - Q_{EG}\\ &= \frac{Q_{EG} \times (a_1 - a_2)}{1 - a_1} = \frac{(a_1 - a_2) \times \sum (q_i \times A_i \times h_i \times D_i)}{(1 - a_1) \times COP}\end{aligned} \tag{11}$$

5.2.2. Calculation on incremental effects of renewable energy application

Here, the incremental effects produced by the solar water heating system and solar photovoltaic system application on green buildings are analyzed as follows.

5.2.2.1. Energy conservation amounts of solar water heating system application. According to the related literature [28], energy conservation amounts of solar water heating system application can be calculated as follows:

$$\Delta Q_{HW} = Q_w \times c_w \times (t_{\text{end}} - t_i) \times f \tag{12}$$

$$\Delta Q_2^E = \frac{\Delta Q_{HW}}{\lambda} \tag{13}$$

where Q_w represents the annual total water consumption amounts (kg); c_w represents specific heat capacity of water at constant pressure, the value is 4.1868 kJ/(kg °C); t_{end} represents the final water temperature in the storage tank (°C); t_i represents the initial water temperature(°C); f represents the assurance rate of the solar energy, the value usually is 0.3–0.8; λ represents the conversion coefficient between energy and power.

5.2.2.2. Energy conservation amounts of solar photovoltaic system application. According to the related literature [29], energy conservation amounts of solar photovoltaic system application can be calculated as follows:

$$\Delta Q_{LE} = J_T \times A_C \times \eta \tag{14}$$

$$\Delta Q_3^E = \frac{\Delta Q_{LE}}{\lambda} \tag{15}$$

where J_T represents the amounts of annual solar radiation in the area (kJ/m^2); A_C represents the lighting area of solar photovoltaic array (m^2); η represents the conversion efficiency of photovoltaic array.

5.2.3. Calculation on total incremental economic benefits

Assume that power price for civil use is P_E and market price of standard coal is P_M in the area where green buildings are located, thus total incremental economic benefits brought by the EETA of the GBEES in every year can be calculated as follows:

$$\begin{aligned}\Delta B_E &= \frac{\Delta Q_M^W}{1000} \times P_M + \Delta Q_E \times P_E\\ &= \frac{(HI_1 - HI_2) \times A \times Z}{1000 \times Eff \times H} \times P_M + \left(\Delta Q_1^E + \Delta Q_2^E + \Delta Q_3^E\right) \times P_E\end{aligned} \tag{16}$$

Table 3
Analysis result of the incremental costs in the FSWCP.

Item	Activity	Subentry incremental costs ($/m^2)	Total incremental costs ($/m^2)
Earlier stage of project	Project consultancy, design identification and so on	2.82	2.82
Land-saving and outdoor environment	Natural ventilation simulation	0.29	2.44
	Roof greening	0.51	
	Permeable pavement	1.64	
Energy saving and utilization	Townhouse building's envelopes structure energy conservation	11.26	28.58
	High-rise building's envelopes structure energy conservation	11.22	
	Renewable energy utilization	6.10	
Water saving and utilization	Water recycling and rain collection	4.05	6.95
	Water quality abandon flow device	0.35	
	Rain filter	2.04	
	Water quality security	0.51	
Material saving and utilization	Material conservation	0	0
Indoor environment quality	Building sound insulation—individual wall	1.23	10.80
	Building sound insulation—floor	9.57	
Operation and maintenance	Intelligent technology	1.10	1.10
Total		52.69	52.69

5.3. *Analysis on incremental environmental benefits of the GBEES*

5.3.1. *Coal-saving amounts of the GBEES*

At present, residential using power in China is mainly from the coal-fired power. Standard coal-power conversion coefficient issued by the National Bureau of Statistics of China is 0.404, which means 0.404 kg standard coal can produce 1 kW h power. This conversion coefficient will be used in the following calculation. If all the power is produced by the coal, applying Eqs. (11), (13) and (15), the amounts of standard coal saving brought by the EETA of the GBEES can be calculated as follows:

$$\Delta Q_M^E = 0.404 \times \Delta Q_E = 0.404 \times \left(\Delta Q_1^E + \Delta Q_2^E + \Delta Q_3^E\right) \tag{17}$$

Then, total amounts of standard coal saving brought by the EETA of the GBEES can be calculated as follows:

$$\Delta Q_M = \Delta Q_M^W + \Delta Q_M^E \tag{18}$$

5.3.2. *Reduction amounts of pollutants emission of the GBEES*

The pollutants of standard coal combustion include carbon dioxide (CO_2), sulfur dioxide (SO_2), nitrogen oxides (NO_x) and so on. According to the discharge coefficient of standard coal combustion and Eq. (18), the reduction amounts of pollutants emission of the GBEES can be calculated as follows:

$$\Delta Q_j^P = \Delta Q_M \times \alpha_j \tag{19}$$

where ΔQ_j^P represents the reduction amounts of the jth type pollutant discharge when standard coal is combusted; α_j represents the discharge coefficient of the jth type pollutant when standard coal is combusted.

5.3.3. *Analysis on incremental environmental benefits of the GBEES*

Due to different discharge prices or charge standards of different pollutants, now assume that the discharge price or charge standard of each pollutant is P_j, the incremental environmental benefits of pollutants emission reduction by the GBEES can be calculated as follows:

$$\Delta B_H = \sum \Delta Q_j^P \times P_j \tag{20}$$

6. Case analyses

6.1. *Project background*

The Fourth Stage of Wanke City Project (FSWCP) in Shenzhen of southern China, covers a floor area of about 96,000 m^2 and mainly includes townhouse buildings and high-rise buildings, with totally 890 sets of households, and 124,700 m^2 architecture areas. This project has participated in the review of "The national ten key energy efficiency project–green buildings comprehensive demonstration project", "The sustainable demonstration project of China and Holland", which is recognized by both the Ministry of Housing and Urban–Rural Development (MOHURD) and Holland Housing Ministry, as well as the "Ministry of Housing and Urban–Rural Development green building three star-level design identification" since the July 2005. It also won the "Green residential building three-star level design label and operation label" issued by the MOHURD in 2008 and 2011, respectively.

The major technological objectives and indexes of the FSWCP include:

(a) the energy conservation rate is 65%;
(b) the proportion of renewable energy accounting for total energy consumption reaches more than 5%;
(c) reuse rate of recycled water reaches 30%;
(d) the utilization rate of water-saving appliances reaches 100%;
(e) living garbage classification collection rate reaches more than 70%, and living garbage recycling utilization reaches more than 30%;
(f) sound insulation and noise reduction can meet the national standard requirement;
(g) decoration material can meet the national standard;
(h) no occupation of high quality cultivated land and the natural reserve land; and
(i) protecting the native landscape and the surface soil.

6.2. *Analysis on the incremental costs of the GBEES*

In order to simplify the analysis, only the incremental costs of the GBEES relative to the BBEES in the construction period are analyzed in this case. The analysis results on incremental costs of unit architecture area in the FSWCP are shown in Table 3. From Table 3, the unit incremental costs of whole project are about 52.69$/m^2, the unit incremental costs of this project's EETA are 28.58$/m^2, and total incremental costs of this project's EETA are $3563,926. The proportion of all kinds of project's incremental costs in the FSWCP is shown in Fig. 3, in which the proportion of energy efficiency and energy utilization incremental costs is the biggest, reaching up 54.23%.

Table 4
Air-conditioning load estimation result in the FSWCP.

Building type	Townhouse buildings	High-rise buildings	Commercial and club matching	Kindergarten
Architecture area (m^2)	64,840	59,840	649	3900
Cold load index (W/m^2)	80	50	180	100
Average operation hours of air-conditioning every year (h)	1200	1200	2160	1800

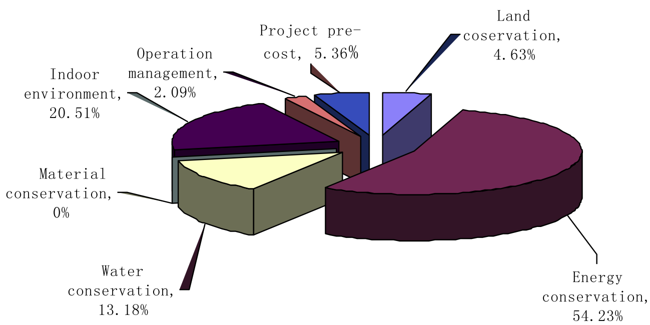

Fig. 3. The proportion of all kinds of project's incremental costs.

6.3. Calculation on the incremental benefits of the GBEES

6.3.1. Incremental economic benefits

The incremental economic benefits in this case mainly brought by air-conditioning power saving in summer, the utilization of solar water heating system and solar photovoltaic system.

6.3.1.1. Saving amounts of air-conditioning power in summer. Because the FSWCP is located in Shenzhen, which belongs to hot summer and warm winter zone, only the benefits of air-conditioning power saving in summer would be considered. The design standard of 65% energy conservation rate is applied in this project; meanwhile the compulsory energy conservation rate is 50% in Shenzhen. The *COP* of this project's air-conditioning system is 2.7. The air-conditioning load estimation results of this project are listed in Table 4.

Apply Eq. (10), the consumption amounts of air-conditioning power in this project are:

$$Q_{EG} = \frac{(80 \times 64,840 + 50 \times 59,840) \times 1200 + 180 \times 649 \times 2160 + 100 \times 3900 \times 1800}{2.7} = 3988,656 \quad (\mathrm{kW\,h})$$

Apply Eq. (11), the saving amounts of air-conditioning power of the GBEES relative to the BBEES every year are:

$$\Delta Q_1^E = \frac{Q_{EG} \times (a_1 - a_2)}{1 - a_1} = \frac{3988,656 \times (65\% - 50\%)}{1 - 65\%} = 1709,424\,(\mathrm{kW\,h})$$

6.3.1.2. Energy conservation amounts of solar water heating system application. According to project related documents, solar energy heat water system application can provide hot water for residences in 260 days every year, 4 h every day on average. This project adopts the household solar energy water heater in the Townhouse buildings in the residential area, and solar energy water heater can heat 72,660 L water from 15 °C to 40 °C every day of the annual 260 days. Assume that solar energy assurance rate *f* is 0.55 and applying Eq. (12), then energy conservation amounts of solar water heating system application can be calculated as follows:

$$\Delta Q_{HW} = Q_w \times C_w \times (t_{\mathrm{end}} - t_i) \times f = 72,660 \times 260 \times 4.1868 \times (40 - 15) \times 0.55 = 1087,561,075\,(\mathrm{kJ})$$

The conversion coefficient of energy-power (λ) is 3600 kJ/kW h. So, applying Eq. (13), power conservation amounts of solar water heating system application can be calculated as follows:

$$\Delta Q_2^E = \frac{\Delta Q_{HW}}{\lambda} = \frac{1087,561,075}{3600} = 302,100 \quad (\mathrm{kW\,h})$$

6.3.1.3. Energy conservation amounts of solar photovoltaic system application. In Shenzhen, annual solar radiation is 4200–5400 MJ/m^2, annual average sunshine duration is around 2000–2200 h, and solar energy can be utilized by an average of 300 days every year. Therefore, Shenzhen is one of the regions which are suitable for solar energy utilization. In this case, assume that annual solar radiation is 4200 MJ/m^2, annual average sunshine hours are 2000 h, and the conversion rate of photovoltaic array is 15%. Considering the building layout and building forms in this residential area, 3000 m^2 solar photovoltaic arrays can be installed on the roofs of 8 high-rise buildings or a kindergarten. So, applying Eq. (14), the power generated by 3000 m^2 solar photovoltaic arrays can be calculated as follows:

$$\Delta Q_{LE} = J_T \times A_C \times \eta = 4200,000 \times 3000 \times 15\% = 1890,000,000 \quad (\mathrm{kJ})$$

Then, applying Eq. (15), power conservation amounts of solar photovoltaic system application can be calculated as follows:

$$\Delta Q_3^E = \frac{\Delta Q_{LE}}{\lambda} = \frac{1890,000,000}{3600} = 525,000 \quad (\mathrm{kW\,h})$$

6.3.1.4. Total incremental economic benefits of the GBEES. Summarize the calculated results above, and then annual total power-saving amounts of the GBEES are:

$$\Delta Q^E = \Delta Q_1^E + \Delta Q_2^E + \Delta Q_3^E = 1709,424 + 302,100 + 525,000 = 2536,524 \quad (\mathrm{kW\,h})$$

At present, power price for civil use is 0.10$/kW h in Shenzhen, so the incremental economic benefits brought by the annual power-saving amounts are:

$$\Delta B_E = \Delta Q^E \times P_E = 2536,524 \times 0.10 = 253,652 \quad (\$)$$

6.3.2. Incremental environmental benefits

According to the calculated results of power-saving amounts and applying Eq. (17), annual coal saving amounts of the GBEES are:

$$\Delta Q_M^E = 0.404 \times \Delta Q_M^E = 0.404 \times 2536,524 = 1024,756\,(\mathrm{kg})$$

According to the related references [30–33], pollutant discharge coefficients of standard coal combustion are shown in Table 5.

Table 5
Pollutant discharge coefficients of standard coal combustion.

Discharge pollutants	Measure unit	Discharge coefficient
Carbon dioxide CO_2	t/t standard coal	2.493
Sulfur dioxide SO_2	t/t standard coal	0.033
Nitrogen oxide NO_x	t/t standard coal	0.0038
Smoke dust	t/t standard coal	0.0096

Table 6
Discharge fees of atmospheric pollutants.

Pollutants type	Discharge fees ($/t)
CO_2	23.46
SO_2	2932.55
NO_x	92.61
Smoke dust	40.35

Applying Eq. (19), annual emission amounts of pollutants of the GBEES can be calculated as follows:

$$\Delta Q_{CO_2} = \frac{2.493 \times 1024,756}{1000} = 2554.7\,(\mathrm{t})$$

$$\Delta Q_{SO_2} = \frac{0.033 \times 1024,756}{1000} = 33.8\,(\mathrm{t})$$

$$\Delta Q_{NO_x} = \frac{0.0038 \times 1024,756}{1000} = 3.9\,(\mathrm{t})$$

$$\Delta Q_{SMOKE} = \frac{0.0096 \times 1024,756}{1000} = 9.8\,(\mathrm{t})$$

According to the related references [34–37], the discharge fees of atmospheric pollutants of standard coal combustion are shown in Table 6.

According to the Table 4 and applying Eq. (20), the incremental environmental benefits of annual pollutants emission due to the GBEES can be calculated as follows:

$$\Delta B_H = (2554.7 \times 23.46 + 33.8 \times 2932.55 + 3.9 \times 92.61 + 9.8 \times 40.35) = 159,810\,(\$)$$

6.4. Cost–benefit evaluation of the GBEES

6.4.1. The evaluation cycle of this project

In this case study, the FSWCP would be assumed to have a design lifetime of 50 years; meanwhile energy conservation technical measures of green buildings' envelopes structure have a design lifetime of 25–30 years, and renewable energy technical equipments have a design lifetime of 15 years. Due to different design lifetimes of different evaluating objects, therefore, the minimum lifetime of 15 years is assumed as evaluation cycle in this project.

6.4.2. Cost–benefit evaluation

The cost–benefit evaluation of the GBEES would be conducted from two aspects: financial evaluation aspect and national economy evaluation aspect. The incremental costs of the GBEES in this project are $3563,926. From the financial evaluation perspective, the annual benefits of the GBEES just include incremental economic benefits ($253,652). From the national economy evaluation perspective, the annual benefits of the GBEES do not only include the annual incremental economic benefits ($253,652), but also include the annual incremental environmental benefits ($159,810); that is to say, the annual national economic benefits are $413,462. Then, Eqs. (1) and (2) are applied to evaluate the cost–benefit of this project's GBEES, which is shown in Table 7.

6.4.3. Discussion about the evaluation results

According to Construction Project Economic Evaluation Method and Parameters [25], the i_c before finance and tax is 8% in some related sectors such as heating and power plant engineering, thermal power generation engineering and central heating engineering. So, 8% is taken as the specific value of the i_c of the EETA on green buildings. In Table 7, if just consider the incremental economic benefits, the ΔIRR of the GBEES is 0.83%, which is far less than the i_c. Thus, the financial evaluation conclusion of this project is not acceptable to private investors. However, if consider both the incremental economic and environmental benefits, the ΔIRR of the GBEES is 7.89%, which is nearly ten times than 0.83% and a little less than the i_c. Thus, the national economic evaluation conclusion of this project is barely acceptable to private investors. The primary cause resulting in this kind of evaluation results is that the EETA on green buildings can bring favorable incremental environmental benefits which cannot be acquired by private investors such as real estate developers and commodity house buyers. Therefore, the government should implement the economic incentive policies based on the incremental environmental benefits brought by the EETA on green buildings to encourage real estate developers to develop the green buildings, and private investors to buy the green buildings. (Note: Due to lack of related authoritative reference, we do not give the specific value of the P_c (the basic investment payback period), and do not conduct a discussion about the P_t of this case study accordingly.)

6.5. Financial sensitivity analysis

Many factors would influence the cost–benefit evaluation results of the GBEES. In this case study, the factors such as the unit incremental costs, power price, pollutants' emission discharge fees, and GBEES lifetime would be regarded as important factors, to analyze the sensitive factors of financial evaluation indexes of the EETA on green buildings.

6.5.1. The unit area incremental costs

Now, assume that the unit area incremental costs of the GBEES change, while other influence factors keep constant, the influence of unit area incremental costs' changing on financial evaluation indexes is shown in Table 8.

From Table 8, it can be seen that, if only the incremental economic benefits would be considered, even if unit incremental costs drop by 30%, the ΔIRR is just 5.81%, and it is very difficult to attract private investors; if the incremental economic and environmental benefits would be considered at the same time, even if unit incremental costs drop by 15%, the ΔIRR can reach 10.66%, and the project has the certain attraction to private investors. Combined with the basic situations of green buildings' development in China, unit incremental costs of the EETA on green buildings dropping by 15% are very easy to realize in the future.

6.5.2. The power price

Now, assume that power price of civil use changes every year, while other influence factors keep constant, the influence of power price annual average changing rate on financial evaluation indexes is shown in Table 9.

From Table 9, it can been seen that, if only the incremental economic benefits would be considered, even if annual increase rate of power price reaches 8%, the ΔIRR is just 7.84%, which is less than the i_c, so it has a little difficult to attract private investors; if the incremental economic benefits and environmental benefits would be considered at the same time, even if the annual increase rate of power price only reaches 3%, the ΔIRR can reach at 9.64%, which is greater than the i_c, so the project has certain attraction to private investors. Therefore, if the government could provide suitable

Table 7
Cost–benefit evaluation results of the GBEES.

Evaluation perspective	Incremental costs ($)	Incremental benefits ($)	ΔP_t (year)	ΔIRR (%)
Financial evaluation	3563,926	253,652	14.05	0.83
National economy evaluation	3563,926	413,462	8.62	7.89

Table 8
Unit incremental costs changing influence on financial evaluation indexes.

Changing rate of the unit incremental costs (%)		0%	−10%	−15%	−20%	−30%	−40%
Unit incremental costs ($/m^2)		28.58	25.72	24.29	22.86	20.01	17.15
Just considering the incremental economic benefits	ΔIRR (%)	0.83	2.21	2.99	3.84	5.81	8.25
Considering the incremental economic and environmental benefits meanwhile	ΔIRR (%)	7.89	9.66	10.66	11.77	14.36	17.65

Table 9
Power price changing influence on financial evaluation indexes.

Annual increase rate of power price		0%	3%	5%	8%	10%	12%
Just considering the incremental economic benefits	ΔIRR (%)	0.83	3.46	5.22	7.84	9.59	11.34
Considering the incremental economic and environmental benefits	ΔIRR (%)	7.89	9.64	10.89	12.85	14.22	15.63

Table 10
GBEES lifetime changing influence on financial evaluation indexes.

GBEES lifetime (Year)		15	20	25	30	40
Just considering the incremental economic benefits	ΔIRR (%)	0.83	3.63	5.03	5.81	6.56
Considering incremental economic and environmental benefits	ΔIRR (%)	7.89	9.82	10.68	11.11	11.45

Table 11
Double factors changing influence on financial evaluation indexes.

Changing rate of unit incremental costs	Annual increase rate of power price				
	0%	3%	5%	8%	10%
0%	0.83	3.46	5.22	7.84	9.59
−10%	2.21	4.87	6.64	9.29	11.05
−20%	3.84	6.53	8.32	10.99	12.77
−30%	5.81	8.52	10.33	13.03	14.83
−40%	8.25	11.00	12.83	15.57	17.39

subsidies based on the environmental benefits of the EETA on green buildings, even if the annual increase rate of power price is 3%, the EETA on green buildings can attract private investors well.

6.5.3. The GBEES lifetime

Now, assume that the GBEES lifetime of this project changes and other influence factors are constant, the influence of the GBEES lifetime changing on the financial evaluation indexes is shown in Table 10.

From Table 10, it can been seen that this project's GBEES lifetime changing has a little influence on the ΔIRR. Considering the incremental economic and environmental benefits at the same time, when the GBEES lifetime increases from 15 years to 40 years, the ΔIRR just changes from 7.89% to 11.45%, increasing by 3.56%. Here, the costs of equipment maintenance and replacement with the increase of the GBEES lifetime in this project are not considered; otherwise, the actual increase of the ΔIRR would become more less. Therefore, the GBEES lifetime is not a sensitive factor to the project economic evaluation results.

6.5.4. The power price and the unit incremental costs

Now, assume the double factors of power price and unit incremental costs change, other influence factors are constant, and only the incremental economic benefits are considered, the influence of double factors changing on the financial evaluation indexes is shown in Table 11.

From Table 11, the ΔIRR in the red area are all greater than the i_c, which implies a better potential to attract private investors. Considering the current increase trend of power market price in China, it is very possible that the power price increases by 3–5% every year on average in the future. Therefore, if the unit incremental costs drop by more than 30% and power price of civil use keeps current increase trend meanwhile, even if only the incremental economic benefits are considered, the incremental investment of the EETA on green buildings has a better market attractiveness.

7. Conclusions

This article firstly structures the theoretical framework system of cost–benefit evaluation of the EETA on green buildings; then develops the analysis methods of incremental costs and quantitative calculation formula of incremental benefits of the EETA on green buildings. On basis of these, this article takes the FSWCP as a study case, and conducts the cost–benefit empirical analysis of the EETA on green buildings, and draws the following important conclusions:

(1) The incremental costs of the EETA account for a large proportion of whole green buildings' incremental costs, which are more than 50% in this case.
(2) The EETA on green buildings can not only bring incremental economic benefits, but also bring good environmental benefits. For example, in this case, the incremental economic benefits of the EETA on green buildings are $253,652, while incremental

environmental benefits are $159,810, which equals to 63% of incremental economic benefits.

(3) If only consider the incremental economic benefits of the EETA on green buildings, the financial evaluation indexes show the project has not the market investment potential; if the government provides subsidies based on the incremental environmental benefits brought by green buildings, the EETA on green buildings can attract private investors well.

(4) Among all the factors influencing the financial evaluation results of the EETA on green buildings, the power price is the most sensitive factor, followed by the unit incremental costs, and the GBEES lifetime has the smallest influence. For example, when the annual increase rate of power price is more than 3% and meanwhile the unit incremental costs drop by more than 30%, the EETA on green buildings has a better market attractiveness.

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