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# Economic and Environmental Benefits of Low-cost Passive Low-energy Buildings

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***Abstract***

Energy and environmental issues are the main reasons many countries increasingly emphasize the energy efficiency of buildings. Passive low-energy buildings (PLEBs) emerged as a new trend in the development of the energy efficiency of buildings given their comfort and high energy efficiency. However, cost hinders the promotion of PLEBs in developing areas. This study focuses on buildings in Northwest China. A PLEB was analyzed by introducing the solar heating system as well as its economic and environmental indicators. This study aims to explore the economic and environmental benefits (EEBs) of low-cost PLEBs. First, the structures and parameters of the envelope were confirmed according to the specifications of PLEB and new energy-saving building (ESB) respectively. Second, energy consumption for heating was resolved using the PHHP software package of PLEB and the energy simulation software DeST-h. These methods confirmed the design scheme of the solar heating system of the PLEB and the ESB. Finally, the ESB was used as basis for analyzing the economic performance of the PLEB in terms of incremental cost and annual earnings. Results show that energy consumption for heating in winter and investment in the solar heating system for the PLEB is lower than that for the ESB, whereas the total incremental cost of the PLEB is higher than that of the ESB. These results are based on the premise of guaranteeing indoor thermal comfort in winter. The PLEB has higher EEBs than the ESB when the service life of solar heating systems is used as calculation period. The results of this study have important reference value for the research on low-cost PLEBs in areas with rich renewable resources.

*Keywords:* Passive Low-energy Buildings, Solar Heating System, Economic Performance

## 1. Introduction

Passive low-energy buildings (PLEBs) are the buildings that has "near zero energy consumption, " which was achieved by improving the thermal insulation of buildings and using passive design measures, such as sun-shade and heat recovery, to guarantee indoor comfort. PLEBs have become the development trend in the energy efficiency of buildings by virtue of "comfort, energy saving, and environmental protection." The Project Team of European Passive Housing Building Promotion defines PLEBs as buildings that meet the requirement of indoor thermal environment in winter and summer without adopting the traditional methods of heating and cooling. The earliest standard of PLEBs was drafted by Professor Wolfgang Fest from the German Institute of Housing and Environment and Adamson from the University of Lund [1]. The first PLEB in China was constructed in 2011. As of 2015, 40 buildings have been included in demonstration projects of PLEB. These buildings occupy a total construction area of 400000 $m^2$. The types of buildings include residential houses, office buildings, kindergartens, dormitories, and factories. The summary of experience from demonstration projects promoted China to issue the Guidelines for Passive Low-Energy Green Building (referred to as "the Guidelines") in October 2015. The Guidelines raised higher requirement in building performance and indoor comfort than China's current design standards for the energy saving building (ESB). Cost is one of the challenges to the promotion of PLEBs in China. Thus, technical and economic analyses of a PLEB in the economically underdeveloped area of Northwest China were conducted to prove that PLEB could be low-cost.

## 2. State of art

Solar energy is clean and renewable. Thus, scholars continue to explore the efficient application of solar energy [2] [3]. Previous studies on photovoltaic or photo-thermal systems were focused on the entire system or its components, whereas analysis was centered on performance and economic benefits. Tang et al. [4] conducted a comparative study of two collectors with different tilt-angles from the horizon, wherein one collector was inclined at 22º (SWH-22) and the other at 46º (SWH-46); this study found that the collector tilt-angle of solar domestic water heating system did not significantly influence heat removal from solar tubes to the water storage tank; thus, both systems had almost similar daily solar thermal conversion efficiency but different daily solar and heat gain. Rodríguez-Hidalgo [5]

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proposed a transient simulation method for the optimization of volume design of thermal storage tank. Wang et al. [6] analyzed the thermal performance of solar domestic water heating system. Ozyogurtcu [7] used the simulation software TRNSYS 16 to analyze a solar fresh-air system with heat recovery; the results show that the system can save 86% of primary energy during the heating period with a payback period of 15 years. Scholars also studied PLEBs from a technical and economic point of view. Thormark [8] analyzed the energy consumption of low-energy buildings during their whole life cycle. The ratio of energy consumption in manufacturing materials and equipment to the energy consumption of the service period was 45%, whereas the ratio of energy consumption saved by recovered materials was between 35% and 40%. These calculations were based on a 50-year calculation period. Studies on low-energy buildings mainly focused on technical measures, whereas studies that explored economic performance did not emphasize on cost. Wang et al. [9] studied the technical scheme of PLEBs in the UK; this study optimized the envelope and orientation of a building using the energy simulation software Energy Plus; solar energy simulation software TRNSYS 16 was used to optimize the solar domestic water heating system. Zhu et al. [10] conducted economic performance analysis of technical measures for a zero-energy residential building in Las Vegas, U.S.A.; results showed that high-performance windows, compact fluorescent lamps, high-moisture roofs, and water-cooled condensers can improve economic return. Krartia et al. [11] applied feasible technical measures to near-zero energy buildings in the Middle East and North Africa; results showed that these technical measures can reduce energy consumption by 50%; however, economic performance, which was connected with changes in the incremental cost of these measures, were changeable. Alirezaei et al. [12] first optimized the architecture by improving the energy efficiency of buildings; this study introduced the solar photovoltaic system and electric vehicles as energy storage equipment; PLEBs then achieved 68% more energy savings than traditional buildings. Adhikari et al. [13] conducted a technical and economic analysis of buildings with near-zero energy consumption; this study found that the investment payback period was 18 years and 14 years when a solar photovoltaic system was in place. Ma et al. [14] compared energy consumption and operational costs before and after the renovation of an office building in Tianjin, China; this study demonstrated that the energy consumption of the renovated building met the requirements for PLEBs. Energy consumption was reduced by 31.5% and running cost by 69%. Zeiler et al. [15] studied PLEBs in the Netherlands; this study showed that the disadvantage of these building was the extremely high initial cost and the low efficiency of solar photovoltaic systems with shield in the south; the advantage of these buildings was the minimal additional cost for new buildings if future legislative restrictions and carbon emission taxes force expensive retrofits in inefficient buildings. Kneifel et al. [16] used statistical methods to establish a regression equation for predicting the performance of low-energy buildings; the regression equation was verified using energy simulation software. Fong et al. [17] used a solar photovoltaic system to show that three-layer residential buildings in areas with extremely high construction density, such as Hong Kong, can be transformed to PLEBs; these buildings should be located in low-density construction areas, such as suburbs. A limited number of studies examined the economic feasibility of PLEBs in economically underdeveloped areas. To address this gap, the present study uses a fully optimized design of solar heating system to examine the feasibility of low-cost PLEBs in economically underdeveloped areas, such as Northwest China.

The rest of this study is arranged as follows. Section 3 establishes the models of the PLEB and the ESB and this section also discusses the design scheme of solar heating systems and the calculation method of relevant parameters. Section 4 calculates the incremental cost and energy savings according to the simulation results of energy consumption and the relevant parameters of solar heating systems. The analysis of the economic and environmental indicators of PLEBs was based on these factors. The feasibility of low-cost PLEBs is discussed in the last section.

## 3. Methodology

### 3.1 Study object

The study site is located in Xining City, Qinghai Province, China. The meteorological data of this area are shown in Figure 1. The climate is characterized by "freezing winter and cool summer," which indicates the need for a heating system in the winter, but no air-conditioning is required during summer. Only the heating consumption of buildings was considered given the uncertainty of energy consumption for lighting. Heating time in Xining lasts from October 5 of the current year to April 15 of the following year, which is equivalent to a total of 193 days. During this time, the climate of Xining is dry with low rainfall. Given the high level of solar radiation, solar heating systems were chosen as resources of renewable energy. The research object is a PLEB pilot project, which is a single-layer residential building. The height is three meters with a total construction area of 271.2 m$^2$. Two families reside in this building. Figure 2 shows the architectural plan of the building. The model for the PLEB was first established according to the Guidelines. The model for the ESB was assessed against the requirements. Finally the economic and environmental benefits (EEBs) of the solar heating system were analyzed.

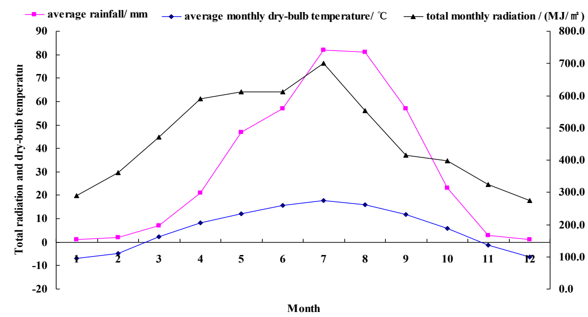


**Fig. 1.** Meteorological parameters of Xining area

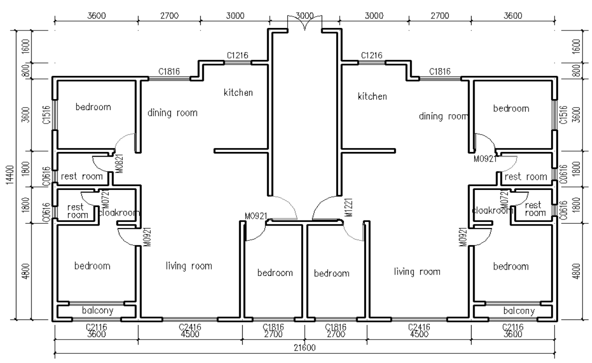


**Fig. 2.** Architectural plan of the building

### 3.2 Design of the envelope

The structure and thermal performance parameters of the envelope of the PLEB were determined according to the performance requirements of the Guidelines (Table 1). The heat transfer coefficient was tested on-site (Figure 3). According to the Design Standard for Energy Efficiency of Residential Buildings in Severe Cold and Cold Zones (JGJ26-2010), residential buildings in Xining belong to Severely Cold Area C. Table 2 shows the limits of the thermal parameters of the envelope. The envelope of the ESB was confirmed based on these limits (Table 3).

**Fig. 3.** On-site test equipment of heat transfer coefficient

**Table 1.** Structure and relevant parameters of the envelope of the PLEB

| Component | Structure | Thickness (mm) | Thermal conductivity coefficient (W/(m·k)) | Heat transfer coefficient (W/(m$^2$·k)) |
|---|---|---|---|---|
| **External wall** | Internal coating | 20 | 0.93 | 0.146 |
| | Fundamental wall | 200 | 1.74 | |
| | EPS insulation board | 300 | 0.046 | |
| | Exterior coating | 20 | 0.93 | |
| **Roof** | Internal coating | 20 | 0.93 | 0.106 |
| | Roof board | 100 | 1.628 | |
| | XPS insulation board | 300 | 0.033 | |
| | Slope making layer | 30 | 0.93 | |
| | Leveling blanket | 20 | 0.93 | |
| | Water poof layer | 10 | 0.17 | |
| **Floor** | Floor tile | 80 | 3.489 | 0.125 |
| | Dry cement mortar | 20 | 0.93 | |
| | XPS insulation board | 250 | 0.033 | |
| | Fine aggregate concrete | 60 | 1.547 | |
| **External window** | Triple glazing with argon filled (6Low−E + 12A + 6 + 12A + 6) | - | - | 0.81 |
| | Plastic window frame | - | - | |

**Table 2.** Limit values of the thermal performance parameters for the envelope in severely cold Area C

| Component | | | Index | Number of building stories | | |
|---|---|---|---|---|---|---|
| | | | | ≤ 3 | 4-8 | ≤ 9 |
| Roof | | | Heat transfer coefficient (W/(m$^2$·k)) | 0.3 | 0.4 | 0.4 |
| External wall | | | | 0.35 | 0.5 | 0.6 |
| Overhead or cantilever floor slab | | | | 0.35 | 0.5 | 0.5 |
| Non-heating basement ceiling | | | | 0.5 | 0.6 | 0.6 |
| External window | Ratio of the window area to the wall area | ≤2.0 | - | 2.0 | 2.5 | 2.5 |
| | | (0.2, 0.3] | | 1.8 | 2.2 | 2.2 |
| | | (0.3, 0.4] | | 1.6 | 2.0 | 2.0 |
| | | (0.4, 0.45] | | 1.5 | 1.8 | 1.8 |
| Surrounding ground | | | Thermal resistance coefficient ((m$^2$·k)/W) | 1.1 | 0.83 | 0.56 |
| External wall of basement | | | | 1.2 | 0.91 | 0.61 |

**Table 3.** Structure and relevant parameters of the envelope of the ESB

| Component | Structure | Thickness (mm) | Thermal conductivity coefficient (W/(m·k)) | Heat transfer coefficient (W/(m²·k)) |
|---|---|---|---|---|
| External wall | Internal coating | 20 | 0.93 | 0.342 |
| | Fundamental wall | 200 | 1.74 | |
| | EPS insulation board | 120 | 0.046 | |
| | Exterior coating | 20 | 0.93 | |
| Roof | Internal coating | 20 | 0.93 | 0.296 |
| | Roof board | 100 | 1.628 | |
| | XPS insulation board | 100 | 0.033 | |
| | Slope making layer | 30 | 0.93 | |
| | Leveling blanket | 20 | 0.93 | |
| | Water proof layer | 10 | 0.17 | |
| Floor | Floor tile | 80 | 3.489 | 1.295 (Thermal resistance coefficient, (m2·k)/W) |
| | Dry cement mortar | 20 | 0.93 | |
| | XPS insulation board | 40 | 0.033 | |
| | Fine aggregate concrete | 60 | 1.547 | |
| External window | Double glazing with Low-E glass (6Low−E + 12A + 6) | - | - | 2.0 |
| | Plastic window frame | - | - | |

### 3.3 Calculation of energy consumption for heating

#### 3.3.1 Calculation of PLEB

Passive house planning package (PHPP) was developed by the Passive House Institute in Germany. This software was designed specifically for passive houses. PHHP uses tables for calculation based on the specification requirements of PLEB. PHHP can be used in the design stage to execute detailed calculation of building energy consumption and assess whether the target building meets the specification requirements of PLEB. PHPP can be used to optimize the design of the envelope and equipment to maximize environmental and economical benefits. PHHP is an auxiliary tool used when applying for PLEB certification. China is yet to develop a special design and evaluation software for PLEB. The Guidelines was established based on German PLEB standards by considering local climate and geographical characteristics. The calculation and evaluation methods for PLEB are the same, but the indicators for energy consumption and specific building materials or equipments differ. Given these differences, PHPP was used to design and evaluate the case used in this study. The functions of PHPP involve energy consumption simulation and the design of envelope and equipments, which include exterior windows, exterior walls, roofs, floors, shades, ventilation, and heating, cooling, and solar application systems. Energy consumption for heating was calculated by PHPP on monthly or yearly basis. In the yearly method, the values of the parameters for outdoor environment are the annual averages during the heating period, whereas the values in the monthly method are the monthly averages.

#### 3.3.2 Calculation of ESB

DeST-h, a simulation software for energy consumption, was adopted in this study to perform the dynamic analogue simulation for the ESB. The model is shown in Figure 4. DeST-h is the assembly of simulation toolkit of thermal environment of residential buildings, which is mainly used to analyze thermal features, predict room temperature, calculate heating and cooling loads, and analyze the economic performance of terminal equipments.

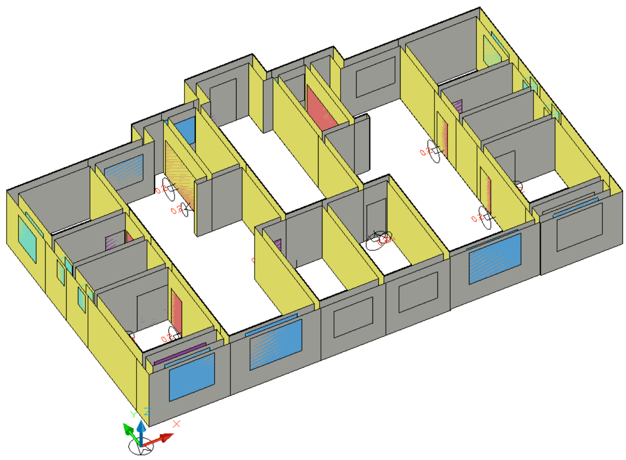

**Fig. 4.** Model of the ESB for the simulation of energy consumption

### 3.4 Solar heating system

The solar heating system (Figure 5) used in this study includes an indirect system with a single water tank. The heat collectors of this system were LPDHWS-2-Y with U-shaped heat pipes, which were produced by Linuo Paradima Co., Ltd. A set of heat collectors was measured 1393 mm ×1453 mm with a total area of 2.02 m$^2$. These heat collectors consist of 12 heat tubes vertically arranged in parallel.

The calculation formula of area of heat collector is given as:

$$A_{IN} = A_C\left(1 + \frac{U_L \cdot A_C}{U_{hx} \cdot A_{hx}}\right) \quad (1)$$

where, $A_{IN}$ denotes the total area of heat collectors needed by indirect system (m$^2$); $A_C$ denotes the total area of heat collectors needed by direct system (m$^2$); $U_L$ denotes the total heat loss of heat collector (W/(m$^2$·ºC)); $U_{hx}$ denotes the heat transfer coefficient of heat exchanger (W/(m$^2$·°C)), which can be acquired from product specifications and the range of its value is 680 to 1040; $A_{hx}$ denotes the area of the heat exchanger of indirect system (m$^2$), the calculation of which can refers to the "Technical code for solar heating system" (GB20495-2009).

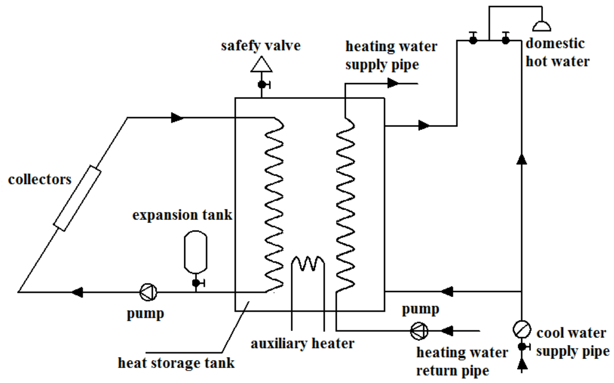


**Fig. 5.** Schematic diagram of the solar heating system

$$A_C = \frac{86.4 Q_H f}{J_T \eta_{cd}(1-\eta_L)} \tag{2}$$

where, $Q_H$ denotes the heat consumption (W); $f$ denotes the solar fraction; $J_T$ denotes the daily solar radiation on the surface of heat collector (kJ/(m$^2$·d)); $\eta_{cd}$ denotes the average efficiency of heat collector (%); $\eta_L$ denotes the heat loss rate of pipes and thermal storage tanks (%).

## 4. Analysis and Discussions of Results

### 4.1 Calculation of energy consumption for heating

Table 4 shows the calculation results of PHHP. Given the accuracy of calculation, the monthly method was selected over the annual method for calculating energy consumption for heating. The result obtained was 16.9 kWh/(m$^2$·a), which met the requirements of the Guidelines (≤18 kWh/(m$^2$·a)). Average thermal load during the heating period was 3.09 W/m$^2$. The simulation results of DeST-h showed that the annual energy consumption for heating of ESB was 40.68 kWh/(m$^2$·a) and the average thermal load was 8.76 W/m$^2$. Figure 6 showed the annual hourly heating load.

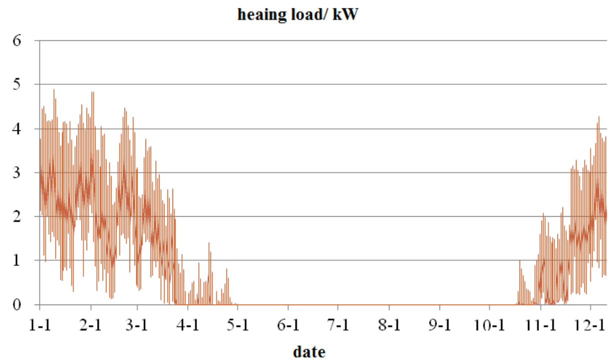


**Fig. 6.** Annual hourly heating load

**Table 4.** Annual energy consumption for heating of the PLEB obtained through PHPP (Unit: kWh/(m$^2$·a))

| Method | Heat loss | | Heat gain | | Heating demand |
|---|---|---|---|---|---|
| | Envelope | Ventilation | Solar | Interior heat resources | |
| Yearly | 41.1 | 8.2 | 21.6 | 11.2 | 18.1 |
| Monthly | 50.0 | 9.7 | 31.5 | 13.8 | 16.9 |

**Table 5.** Relevant parameters and results of calculation of the area of heat collectors

| Model | $A_{IN}$ (m$^2$) | $A_C$ (m$^2$) | $U_L$ (W/(m$^2$·°C)) | $U_{hx}$ (W/(m$^2$·°C)) | $A_{hx}$ (m$^2$) | $Q_H$ (W) | $f$ | $J_T$ (kJ/(m$^2$·d)) | $\eta_{cd}$ (%) | $\eta_L$ (%) |
|---|---|---|---|---|---|---|---|---|---|---|
| PLEB | 6.06 | 5.90 | 4 | 860 | 1.03 | 3.09 | 0.5 | 15345 | 0.4 | 0.2 |
| ESB | 18.00 | 16.72 | 4 | 860 | 1.03 | 3.09 | 0.5 | 15345 | 0.4 | 0.2 |

### 4.2 Calculation results of the area of heat collectors

The area of heat collectors can be determined by Formulas 1 and 2 (Table 5). The areas of heat collectors for the PLEB and the ESB were 6.06 m$^2$ and 18.18 m$^2$, respectively.

### 4.3 Incremental cost calculation

The incremental cost of the PLEB mainly involved the insulation board, exterior window, thermal bridge, and the initial cost of solar heating system. The capital below was calculated according to the foreign exchange rate on Monday, November 28, 2016 at 1 Yuan for 0.1449 US dollar. The local market prices for related materials and equipments were: EPS insulation board at 28.98 dollar/m$^2$, triple glazing window with argon filling at 130.41 dollars/m$^2$, and double glazing window at 57.96 dollars/m$^2$. Tables 6 and 7 showed the relevant parameters and calculation results of incremental cost. The equipment was cancelled because the initial investment of heat recovery equipment was high and solar heating was adopted in the project. Incremental cost was then changed to 5456.93 dollars.

**Table 6.** Parameters for the calculation of incremental cost (unit: m$^2$)

| Model | External wall | | | | External window | | | | Roof | Heat collector |
|---|---|---|---|---|---|---|---|---|---|---|
| | East | West | South | North | East | West | South | North | | |
| PLEB | 28.8 | 28.8 | 56.2 | 58.2 | 6.9 | 6.9 | 21.8 | 7.2 | 271.2 | 6.06 |
| ESB | | | | | | | | | | 18.18 |

**Table 7.** Incremental cost of the PLEB (unit: US dollar)

| External wall | External window | Roof | Floor | Handle of thermal bridge | Solar system | Heat recovery equipment | Total |
|---|---|---|---|---|---|---|---|
| 897.22 | 3721.03 | 1963.40 | 2061.64 | 1160.65 | −4347 | 6955.2 | 12412.1 |

### 4.4 Calculation of energy savings
The floor area of the project was 271.2 $m^2$, and the energy consumptions for heating of the PLEB and the ESB were 16.9 kWh/($m^2$·a) and 40.68 kWh/($m^2$·a), respectively. The annual energy saving of the PLEB was 6456.3 kWh on account of the efficiency of solar heating system (0.8). Local electricity price was 0.077 US dollar/kWh. Thus, the annually savings in energy expenditure was 495.82 dollars.

### 4.5 Environmental benefit analysis
Reduction of pollutant emission is a critical factor to the quality of living environment. The formula for calculating this factor is given as [15]:

$$Q = \frac{E_s \times \alpha}{W} \times f \tag{3}$$

where, $Q$ denotes the reduction of pollutant emission (kg); $Es$ denotes the energy saving (kWh); α denotes the heat value of 1 kWh of electricity (3.6 MJ/kWh); $W$ denotes the heat value of standard coal (29.308 MJ/kg); $f$ denotes the pollutant emission factors of 1 kg of standard coal (Table 8).

The PLEB can save 793 kg of standard coal annually. Thus, annual reduction of pollutant emissions included 1958.71 kg of carbon dioxide, 15.86 kg of sulfur dioxide, and 7.93 kg of dust. Disposing the pollutant generated by 1 kg of standard coal cost 0.072 dollar. Annual saving in pollutant disposal was 57.53 dollars.

**Table 8.** Pollutant emission factors of 1kg of standard coal

| Pollutant | Carbon dioxide | Sulfur dioxide | Dust |
|---|---|---|---|
| Emission factors | 2.47 | 0.02 | 0.01 |

### 4.6 Economic benefit analysis
Given the service life of insulation material and solar heating system, the calculation period for internal earnings was set at 15 years (Figure 7). The internal rate of return was 6% with incremental investment of 5456.93 dollars. Annual earnings was 3479.33 dollars, which include annual savings in energy expenses of 3421.8 dollars and annual savings in pollutant disposal of 57.53 dollars. Dynamic payback period was set at 13.2 years when loan interest rate was used as base earnings ratio (4.9%). Internal rate of return is −5% if a heat recovery equipment was installed.

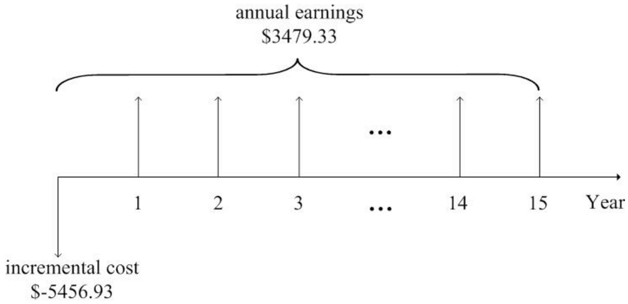


**Fig. 7.** Cash flow diagram

## 5. Conclusions

A PLEB in Northwest China was selected as research object to study the EEBs of PLEBs. The models of PLEB and ESB were established according to the Guidelines and the Design Standard for Energy Efficiency of Residential Buildings in Severe Cold and Cold Zones (JGJ26-2010), respectively. Incremental cost, energy saving, internal rate of return, and pollutant emission of the PLEB were calculated with reference to the ESB. The conclusions are as follows.

(1) The incremental cost of the PLEB is relatively high when ESB was used as reference. The PLEB with high-performance envelope and efficient heat recovery equipment were adopted. Thus, economic performance is poor and the internal rate of return for the calculation period is negative.

(2) An efficient heat recovery equipment with high initial investment can be cancelled after using the solar heating system. This approach decreases incremental cost and improves economic performance. The internal rate of return for the calculation period is higher than that of the loan interest rate (4.9%). The dynamic investment payback period is 13.2 years.

(3) The PLEB based on solar heating system has significant environmental benefit and can effectively reduce carbon dioxide, sulfur dioxide, and dust emission.

Through comparative analysis, this study proved that PLEBs offers EEBs. This study supports the promotion of low-cost PLEBs in economically underdeveloped areas. Service period was used as the calculation period. However, the realistic significance of the results will increase if the entire life cycle is used as the calculation period. This approach is the direction of future studies.

### Acknowledgements
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