Energy Saving Retrofitting of Existing Public Building: A Case Study in Shanghai Area

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Abstract. In order to reduce energy consumption of commercial and public buildings, a series of policies has been implemented in Shanghai area. And retrofitting of inefficient commercial and public buildings serves as one of the main measures. However, there is little study about the effect and economic analysis of energy saving retrofitting, which hinders the popularizing of energy saving retrofitting. Under the sponsorship of the government of Shanghai and World Bank, a typical office building in Changning district of Shanghai was studied about whether it could be retrofitted into a nearly zero energy building through a series of passive and active technologies. During the design stage, based on energy consumption simulations, it was found that nearly zero energy building could save 37.1% energy compared with baseline building. Among the adopted technologies, high-efficiency lamp and photovoltaic system had a relatively higher energy saving ratio, which were followed by high-efficiency cooling and heating system, natural lighting and envelope insulation. Natural ventilation had the least energy saving ratio. By one-year field monitoring of energy consumption after building retrofitting, it was found that the retrofitted building was able to control the CO2 emission per unit area to be less than 25 kg/m²·a, which met the goal of nearly zero energy building. And the incremental cost per unit area of nearly zero energy building is ¥1553 compared to baseline building. High efficiency lighting is the most cost-effective technology. The conclusions drawn in this study could provide reference for similar retrofitting projects in Shanghai area.

1. Introduction

People spend a majority of their lifetime in buildings, and the building energy consumption has become a significant part of the total energy consumption of society. For example, the building energy consumption has accounted for 27.3% and 41.1% of total energy consumption in 2010 for China and America[1]. Thus, it is necessary to reduce the energy consumption of buildings. Statistics suggest that the total construction area of existing buildings in China is more than 58 billion m², and it is still growing at a rate of 2 billion m² a year [2]. What’s more, the energy consumption per unit area of public buildings is more than twice as much as residential buildings [3]. Therefore, energy-saving retrofitting of public buildings has become an urgent task in China. Shanghai, as one of the developed cities in China, plans to support the retrofit of 1.5 million m² of existing buildings and targets to reduce its building energy intensity by 10-20% during a 5 to 10 years’ period [4]. In order to achieve this goal, some demonstration building with nearly zero energy was developed and used to popularize related retrofitted technologies.
The term NZEB was firstly proposed by European Union, which refers to a building that has a very high energy performance that requires nearly zero or a low amount of energy to meet energy demands for heating, cooling, ventilation, hot water and lighting [5]. And it is an important transition step for building to realize Zero-Energy goal. Although different countries established various technical indicators for NZEB based on local climatic and building features, the technology roadmaps are almost the same [6]. Firstly, it has been found that many passive technologies could reduce significantly the total energy demand, such as envelope insulation [7], natural daylight [8]. Thus, these measures are usually adopted in priority. Secondly, many existing public buildings was built decades ago, and the energy systems of them has been out of date, which leads to low energy efficiency. Improving the energy performance of these system is a common practice, including lighting system [9], air conditioning system [10] etc. Finally, renewable energy plays a crucial role in achieving NZEB [11], such as photovoltaic system. The electricity produced by photovoltaic system can be used for the air-conditioning, lighting and other systems within the building.

Based on a retrofitted office building, this paper explored the feasibility of public building to meet the NZEB standard in the climate of Shanghai area. The retrofit scheme of NZEB was first introduced, and the energy consumption of NZEB was simulated based on the software eQUEST-3.64. The energy saving effect of every retrofit technology was analyzed. Then a one-year field monitoring of energy consumption was implemented for the retrofitted building to verify actual energy saving effect of retrofit scheme. At last, the incremental cost of NZEB was analyzed.

2. Method and materials
Shanghai (31.2N, 121.5E), a city located at the west coast of Pacific Ocean and the east rim of Asian continent, belongs to the north subtropical monsoon climate with four different seasons, plenty of sunshine and rainfall. Summer and winter are long while spring and autumn are short. The average air temperature of hottest month (July and August) is up to 28℃, while the average air temperature of coldest month (January) is 4℃. The area of target office building is 2866.2 m², and building height is 12 meters. The rendering is shown in Figure 1. According to the evaluation criteria of World Bank, the CO2 emission standard for NZEB should be less than 25 kg/m²·a when not considering the energy consumption of office equipment and decoration lighting.

![Figure 1. Schematic diagram of target office building.](image)

In order to evaluate the energy performance of NZEB, a baseline building is set up according to the “Design Standard for Energy Efficiency in Public Buildings” (DGJ08-107-2012). In general, the energy consumption of air conditioning and artificial lighting accounts for a large part of total energy consumption. And optimizing the thermal performance of envelope is a common practice [9,10]. The thermal properties of building envelope for NZEB and baseline building are shown in table 1, and the window parameters are shown in table 2.
Table 1. Properties of building envelope.

| Building component | Baseline building | NZEB |
|--------------------|-------------------|------|
| External Wall      | 0.90              | 0.56 |
| Roof               | 0.60              | 0.40 |
| Overhead floor     | 0.90              | 0.53 |
| Floor              | 2.0               | 1.8  |
| Ground             | 0.83              | 0.83 |

Table 2. Properties of building window.

| External window | Baseline building | NZEB |
|-----------------|-------------------|------|
|                 | Window-wall ratio | Shading Coefficient | Window-wall ratio | Shading Coefficient |
| East            | 0.21              | 3.5 | 0.5 | 0.21 | 2.0 | 0.38 |
| South           | 0.28              | 3.5 | 0.5 | 0.28 | 2.0 | 0.38 |
| West            | 0.29              | 3.5 | 0.5 | 0.29 | 2.0 | 0.38 |
| North           | 0.27              | 3.5 | 0.5 | 0.27 | 2.0 | 0.38 |

The setting point of indoor environment, fresh air volume as well as power density of office equipment are the same, as is shown in table 3, so that the energy consumption of both buildings can be compared under the same conditions. For NZEB, high-efficiency lambs are adopted, and the lighting power of both buildings are presented in table 4.

Table 3. Setting point of indoor parameters.

| Room type       | Summer Temperature (°C) | Summer Relative humidity (%) | Winter Temperature (°C) | Winter Relative humidity (%) | Fresh air volume (m³/h/people) |
|-----------------|-------------------------|-----------------------------|--------------------------|-----------------------------|--------------------------------|
| Office room     | 24                      | 50                          | 22                       | —                           | 30                             |
| Meeting room    | 24                      | 50                          | 22                       | —                           | 30                             |
| Reception room  | 24                      | 50                          | 22                       | —                           | 30                             |
| Data Room       | 20~25                   | 45~55                       | 20~25                    | 45~55                       | —                              |

Power density of office equipment: 10 W/m²
Total number of people: 250

Table 4. Lighting power of buildings.

| Room type       | Illuminance (lx) | Baseline Building | NZEB |
|-----------------|------------------|-------------------|------|
| Data room       | 500              | 15                | 11   |
| Meeting room    | 300              | 9.0               | 7    |
| Office room     | 500              | 15                | 11   |
| Lobby           | 300              | 11                | 7    |
| Corridor        | 50               | 4.0               | 3.3  |
| Power supply room | 200              | 9.0               | 7    |
| Pump room       | 100              | 4.0               | 3.5  |
| Machine room    | 100              | 4.0               | 3.5  |

Both buildings adopt Varied Refrigerant Volume (VRV) system, but the detailed parameters are different, as shown in table 5. The operation schedule and occupancy factors are based on the “Design Standard for Energy Efficiency in Public Buildings” (DGJ08-107-2012). In addition, compared with baseline building, NZEB also adopts monocrystal photovoltaic system on the roof. Photovoltaic system not only provide electricity, but also serve as shading and heat insulation component, which could
improve indoor thermal comfort in summer. The total area of photovoltaic panel in this retrofit project is up to 285 m², and system capacity is 50.4 kW. The photoelectric conversion efficiency equals to 17%. The energy produced by photovoltaic system is mainly used for indoor lighting and office equipment. And the surplus electricity is sent back to the grid.

Table 5. Parameters of air condition system for both buildings.

| Item          | Baseline building | NZEB                   |
|---------------|-------------------|------------------------|
| Air conditioning type | multi-split type air conditioner | Indoor temperature <20°C                  |
| Operation condition in winter | Indoor temperature > 26°C |                        |
| Operation condition in summer | Coefficient of performance | 3.70                        |
| Fresh air system | Independent fresh air system | Fresh air system with heat recovery (cooling efficiency:60%; heating efficiency: 65%) |

Moreover, the building has a large window-wall ratio. According to CFD simulation, improving the time of window opening in transition season could make full use of natural free cooling of outdoor air, which contributes to reducing the energy consumption of air conditioning and satisfies the thermal comfort requirement. According to daylight simulation, it is revealed that the lighting of space near to the window could be satisfied by natural light. Therefore, light sensors are considered in the retrofit of indoor illumination. The artificial lighting systems are controlled based on the illuminance measured by the sensor to save energy. In addition, light guide tubes are installed in the room where natural lighting is not available in order to reduce the operation time of artificial lighting, such as washing room. In summary, all the energy saving measures adopted by NZEB are listed in Table 6.

Table 6. Measures of Energy Saving retrofitting.

| Item No. | Measures                                                                 |
|----------|--------------------------------------------------------------------------|
| Item 1   | Increase the insulation level of building envelope to reduce heat gain.   |
| Item 2   | Natural ventilation in transition seasons to make full use of free cooling|
| Item 3   | Natural lighting and light guide tube to reduce energy consumption of artificial lighting |
| Item 4   | High-efficiency light and smart control                                  |
| Item 5   | High-efficiency air conditioner and heat recovery system                 |
| Item 6   | CO2 monitoring                                                           |
| Item 7   | Photovoltaic panel                                                       |
| Item 8   | CO2 monitoring system is installed to determine the fresh air volume.   |
| Item 9   | During the operation period of air conditioning, the windows are closed automatically to reduce unnecessary energy consumption. |
| Item 10  | The air supply and return vents are designed reasonably to avoid temperature gradient or short circuit. |
| Item 11  | Building automatic systems are installed to control air conditioner, lighting equipment, fan, light guide, heat recovery equipment and windows. |
| Item 12  | Sub-metering system of energy consumption is installed to monitor and optimize the operation condition of all sub-systems. |

3. Results and analysis

3.1 Energy saving evaluation based on simulation and field measurements
Based on the simulation results of energy consumption conducted by the software eQUEST-3.64, the detailed energy consumption of NZEB and baseline buildings are shown in Table 7. The monthly energy consumption of both buildings are presented in Figure 2. It can be seen that, except for the energy consumption of equipment, the energy consumption of other systems for NZEB are all much smaller
than baseline building. And the energy consumption reduction of lighting is the largest, which is up to 72.67%. The energy consumption reduction ratio of cooling in summer months are much larger than that of heating in winter months.

![Figure 2. Monthly energy consumption of baseline building and NZEB.](image)

**Figure 2.** Monthly energy consumption of baseline building and NZEB.

**Table 7.** Energy consumption of NZEB and baseline building.

|                      | Baseline building | NZEB  | Reduction ratio |
|----------------------|-------------------|-------|-----------------|
| Energy consumption of cooling (MWh) | 96.1              | 62.26 | 37.15%          |
| Energy consumption of heating (MWh)   | 41.46             | 31.60 | 23.78%          |
| Energy consumption of Equipment (MWh) | 53.20             | 53.20 | 0%              |
| Energy consumption of lighting (MWh)  | 76.10             | 20.80 | 72.67%          |
| Total (MWh)             | 266.9             | 167.9 | 37.1%           |

According to the field measurement data of photovoltaic system, 960 kWh electricity could be produced by 1kW installed capacity in one year. Hence, the total electricity production could be up to 48 MWh per year. Based on simulation results, subtracting the energy consumption of equipment, the energy saving rate of different retrofitting measures are presented in table 8. It can be seen that adopting high-efficiency lamp and photovoltaic panels have an energy saving ratio both more than 20%, which has significant effect on reducing energy consumption. The energy saving ratios of high-efficiency heating and cooling system, nature lighting and improving insulation level of building envelope are almost around 7%. And natural ventilation has the least energy saving effect. According to the empirical equation between CO2 emission and energy consumption (equation (1)), not considering the energy consumption of equipment, the energy consumption and CO2 emission per unit area of both buildings are presented in Figure 3. It’s obvious that the annual CO2 emission per unit area of NZEB is less than 25 kg/m²·a, meeting the evaluation standard of World Bank.

![Figure 3.](image)

**Figure 3.** Annual energy consumption per unit area for baseline building and NZEB (exclusive of energy consumption of equipment): (1) Annual energy consumption per unit area; (2) Annual CO2 emission per unit area.
\[ CO_2 \text{ emission (kg)} = 0.72 \times \text{Energy consumption (kWh)} \] (1)

**Table 8. Energy saving ratio of different retrofitting measures.**

| Item                  | Measures                                                                 | Total energy consumption (MWh) | Energy saving ratio (%) |
|-----------------------|---------------------------------------------------------------------------|-------------------------------|-------------------------|
| Baseline              | —                                                                         | 213.6                         | —                       |
| Nature lighting       | Illumination sensor; Light guide tube                                     | 198.8                         | 6.93                    |
| Building envelope     | Improve insulation performance 20%                                        | 184.9                         | 6.50                    |
| High efficiency lamp  | Choose lamp that has a lower power                                        | 136.4                         | 22.70                   |
| High-efficiency heating and cooling system | The Integrated part load value of VRV system changes from 3.7 to 4.5; Heat recovery system is used. | 120.6                         | 7.4                     |
| Natural ventilation  | Improve natural ventilation and reduce the operation time of air conditioning for 30 days. | 114.7                         | 2.8                     |
| Photovoltaic system  | 285 m² photovoltaic panel is installed.                                   | 66.7                          | 22.5                    |

The building retrofitting was carried out from September 2016 to August 2017. And the energy consumption in September and October after retrofitting was measured and compared with the energy consumption before retrofitting, as shown in Figure 4. It can be found that, except for the energy generation by photovoltaic panel, the energy consumption after retrofitting was less than that before retrofitting, which verifies the efficiency of energy saving retrofitting.

![Figure 4. Energy consumption comparison in September and October before and after retrofitting (except for the energy generation by photovoltaic panel).](image)

A detailed sub-metering of energy consumption for the whole year was also conducted. The period is from 21st Dec. 2017 to 20th Dec. 2018 except for the weekends and national holidays, totally 250 days were counted for the energy consumption evaluation of NZEB. And the detailed energy consumption is presented in table 9. It can be seen that, after one-year operation, the retrofitted building is able to control the carbon emission per unit area to be less than 25 kg/m²·a, which also met the energy saving standard of World Bank. Compared with the simulated carbon emission result (16.75 kg/m²·a), the measured value (24.89 kg/m²·a) is a little higher. Through the field investigation, it was found that the following events also affect the final energy consumption: (1) In order to remove the smell of decoration materials, fresh air handling units have a longer operation period compared to normal condition. (2) The building automatic system launched all the air conditioning system at 8:00 on weekdays no matter whether the room was occupied or not. (3) More air penetrated into the lobby when people pass through the main entrance. (4) The staff used the air conditioning even when outdoor...
environment was comfort. (5) The automatic control system of some windows did not work, leading to more air penetrating into the room. (6) The door and windows of washroom were in open state for a long time, which resulted in more fresh air penetrating into the room. And these problems have been solved in the following building operations. The test results of average illuminance in the main function room is presented in Table 10. It can be found that the measured illuminance was more than twice the design value, which met the lighting requirement of different types of room. From the viewpoint of energy saving, the power of lighting could be reduced properly.

**Table 9.** Measured result of energy consumption and carbon emission for one-year field monitoring.

| Energy consumption | Power | Air conditioning | lighting | Photovoltaic |
|--------------------|-------|------------------|----------|--------------|
| unit               | kWh   | 5846.37          | 98076.14 | 30395.52     |
| Energy consumption | kWh/m²·a | 2.04       | 34.22    | 10.60        |
| Gross energy consumption | kWh/m²·a | 34.56    |         |
| Carbon emission   | kg/m²·a | 24.89       |         |

**Table 10.** Measured result of average illuminance in the main function rooms.

| Room Type          | Illuminance (lx) | Design value (lx) |
|--------------------|------------------|-------------------|
| Training room      | 1088             | 349               | 500               |
| Meeting room       | 1229             | 669               | 300               |
| Senior office room | 1359             | 951               | 500               |
| General office room| 1193             | 625               | 300               |
| Reception area     | 1093             | -                 | 200               |
| Exhibition area    | 778              | -                 | 200               |

3.2. Cost analysis

The cost for each retrofitting measures are shown in Table 11. It can be found that the retrofitting cost of NZEB is about 455000 ¥ higher than that of baseline building, and the incremental cost per unit area is 1553 ¥/m².

**Table 11.** Cost of retrofitting measures for NZEB and baseline buildings.

| Measure                                     | Baseline building renovation cost (10⁴¥) | NZEB investment renovation cost (10⁴¥) |
|---------------------------------------------|------------------------------------------|---------------------------------------|
| Envelope insulation                         | 41.29                                    | 62.45                                 |
| Window and sunshade                         | 225.31                                   | 360.14                                |
| Ground insulation                           | 23.75                                    | 31                                    |
| High-efficiency lighting                    | 16.97                                    | 23.13                                 |
| Solar light guide tube                       | --                                       | 15.99                                 |
| High-efficiency heating and cooling system  | 14.60                                    | 29.00                                 |
| Photovoltaic system                         | --                                       | 56                                    |
| High-efficiency Electric transformer and distribution system | 27.00                                    | 43                                    |
| High-efficiency water pump system           | 45.60                                    | 57.00                                 |
| Heat recovery system                        | --                                       | 61.40                                 |
| Building automatic system                   | 15.14                                    | 85.19                                 |
| Energy metering system                      | --                                       | 30.80                                 |
| Sum                                         | 410                                      | 855                                   |
In addition, it can be seen that the investment of high-efficiency lighting was lower than other technologies except for solar light guide tube, but it has a much higher energy saving ratio (more than 20%). Thus, it was the most cost-effective technology, and should be used in similar retrofit projects. The energy saving ratios of high-efficiency heating and cooling system and envelope insulation are almost the same, however the cost of high-efficiency heating and cooling system was lower than half of the cost of envelope insulation. Hence high-efficiency heating and cooling system was more cost effective than envelope insulation.

4. Conclusions
Energy saving retrofitting of existing buildings has been paid more and more attention in recent years. Under the support of World Bank and government of Shanghai, a typical office building in Shanghai area was retrofitted to verify whether it can meet the requirements of nearly zero energy buildings. 12 retrofitting measures are adopted, including passive and active aspects. The passive technology includes envelope insulation, natural lighting and ventilation etc., while active technology includes high-efficiency machine, variable frequency fan or pump. According to the simulation results of energy consumption, it was found that high-efficiency lamb and photovoltaic system had a relatively higher contribution to saving energy, which were followed by high-efficiency air conditioner, natural lighting and envelope insulation. Natural ventilation had the least contribution to saving energy. After retrofitting, one-year monitoring of energy consumption showed that the CO2 emission per unit area of retrofitted building was less than 25 kg/m²·a, which meets the requirement of nearly zero energy building. The cost analysis shows that the retrofitting cost per unit area of nearly zero energy building is 1553 ¥ more than that of baseline building. And high-efficiency lighting is the most cost-effective technology. The results in this paper could provide reference for energy saving retrofitting of public buildings in Shanghai area. Further survey of more retrofitted building will be carried out in the future to build evaluation index of different retrofit schemes, and guide the promotion of energy-saving retrofit.

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