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# Effect Evaluation of Large-Scale Energy Saving Renovation of Rural Buildings in Beijing and Implications for Other Cities in the Same Zone

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**Abstract:** Compared with that in cities, energy efficiency of rural houses is lagging behind, with high total energy consumption, low efficiency and poor indoor thermal environment. Beijing is the first area to promote the energy-saving renovation of existing rural buildings on a large scale, systematically, at the whole-city level in China. Through government symposiums, field surveys, simulation analysis and other research methods in this article, the implementation scheme and policy system for the energy-saving renovation of rural buildings in Beijing were sorted out, analyzed and evaluated. The following conclusions are drawn: Beijing has completed energy-saving renovations of more than 1 million rural households; the average energy-saving rate of the thermal insulation renovation of rural houses in Beijing is about 30.0%; the average room temperature has increased by 2.6 °C after the renovation; Beijing can achieve the annual energy conservation of 590,000 tons of standard coal by the end of 2016 after the insulation renovation work of 710,000 rural houses. Beijing's experience with the energy-saving renovation of rural building envelopes should lead to further analysis, verification and optimization in other similar climatic zones, and the average energy-saving rate in the promoted cities can achieve 30.0% above.

**Keywords:** rural building; energy-saving renovation; thermal environment

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**Citation:** Deng, Q.; Shan, M.; Zhang, G.; Zhang, S.; Liu, Y.; Yang, X. Effect Evaluation of Large-Scale Energy Saving Renovation of Rural Buildings in Beijing and Implications for Other Cities in the Same Zone. *Sustainability* **2023**, *15*, 5580. https://doi.org/10.3390/su15065580

Academic Editors: Yuanda Cheng, Hanna Jędrzejuk, Peng Xue and Ji Li

Received: 30 January 2023
Revised: 18 March 2023
Accepted: 21 March 2023
Published: 22 March 2023



## 1. Introduction

Since China has recently pledged to achieve carbon emissions peak and neutrality by 2030 and 2060, respectively; carbon reduction speed tends to accelerate as urgent requirements. In 2018, $CO_2$ emissions from the building sector accounted for 20% of total carbon emissions in China [1], as shown in Figure 1. Under the carbon emission targets, the building sector needs to improve building energy efficiency and promote building electrification [2,3]; this is particularly important in rural areas because its building energy consumption accounts for more than 20% of the total building energy consumption. China has made considerable progress in enforcing building energy regulations and improving the efficiency of existing buildings and the district heating network. With continuous urbanization in China, the development priorities in rural areas have changed from meeting basic housing demands 30 years ago to providing for more comfortable and secure accommodation and pursuing ecological development. Rural residential buildings are very different from urban buildings in China. Compared with that in cities, energy efficiency of rural houses is lagging behind, with high total energy consumption, low efficiency and poor indoor thermal environment [1,4]. Northern rural homes are usually one- or two-story buildings with courtyards, scattered distribution and independent heating control [5,6], while the most common urban residential buildings are high-rise apartment buildings with full-space and continuous heating. Design and construction of rural houses varies by climate conditions. Single-story homes are typical in northern China, while rural buildings in southern China are normally two stories and more open, with natural ventilation [4]. In addition to the low combustion efficiency of scattered coal burning, the lack of insulation measures and poor air-tightness of the building envelope in rural houses are also important factors for the high energy consumption and difficulty in improving comfort in housing. The Ministry of Housing and Urban-Rural Development (MOHURD) formally announced a code for rural buildings in December2012 [7]. In 2017, Chinese central government began the policy for clean heating pilot city in northern China [8–10], promoting clean heating instead of scattered coal burning while renovating existing buildings for better energy conservation. A total of 88 clean heating pilot cities were selected through a competitive review. Multiple studies evaluating the pilot work effect in the past few years [11–15] show that certain problems exist in the pilot programs of rural residential energy efficiency improvement, such as insufficient planning, inadequate task load, slow implementation progress and low task completion rates.

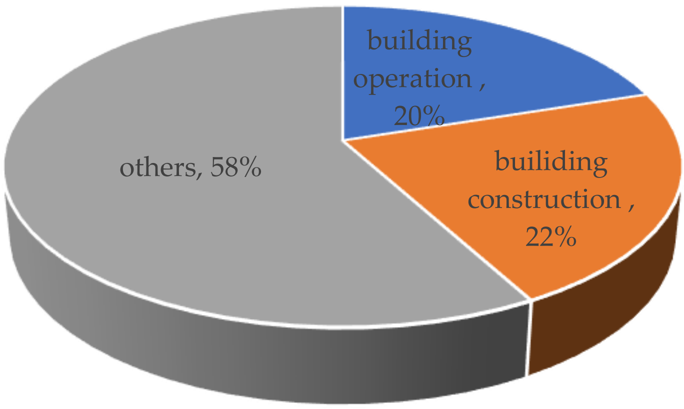


**Figure 1.** $CO_2$ emissions from building construction sector in China [1].

Properly carrying out energy-saving renovations of rural residential building envelopes can not only improve the overall effectiveness of clean heating initiatives in the north, but also help China achieve carbon neutrality and carbon emission peak. On 24 October 2021, the State Council issued the latest Notice [16], pointing out that for the urban and rural carbon peaking efforts, it is necessary to promote low carbon transformation in rural construction and energy use, including promoting the construction of green rural housing and accelerating the energy-saving renovation of rural housing. The Ministry of Housing and Urban-Rural Development (MOHURD) and the National Development and Reform Commission (NDRC) issued the document proposes to promote rural housing winter clean heating projects in the northern region while conducting energy-saving renovation to improve the comfort of frequently-used rooms and, after renovation, achieve 30% higher energy efficiency or more [17].

The authors' team has been participating in various pilot projects of energy-saving renovation for rural housing in Beijing since 2005, pioneering hundreds of pilot projects and carrying out research on related technical solutions and effect evaluation [18,19]. These include field assessments and simulation analyses of post-renovation indoor thermal comfort improvements and energy-saving effects; comparative analyses of specific technical solutions such as roofs, exterior walls, exterior windows and passive solar rooms; studies of the contributions to reducing coal consumption and pollution emissions, etc. In those projects, more than 500 rural residential dwellings were renovated. Retrofitted houses have satisfying results, in which an average indoor air temperature is above 15 °C [20]. However, the above-mentioned studies focus only on a small-scale of, or the intermediate process for, regional pilot projects. Since 2008, Beijing has continuously performed large-scale renovation on rural housing for anti-seismic and energy-saving purposes by drawing on past technical roadmaps and key technoeconomic parameters. The Beijing government has developed a long-term renovation policy. Nearly 332,000 new and existing rural residential buildings in Beijing have been renovated. The average annual heating can save 1.5–2.5 tons of coal per house, i.e., 46,000 tce ($1.3 \times 10^7$ GJ) in coal use [20]. As of the end of 2018, more than 1 million rural homes in Beijing have undergone energy-saving renovations, which has established Beijing and even all of China as a leader in energy conservation. In terms of popularizing model and scale, Beijing has long been a domestic pioneer in energy-saving renovations for existing rural homes.

In order to serve as a model for other rural communities in cold climate zones and to achieve the dual-carbon objective and other future targets, this article analyzes and evaluates the implementation strategy and overall renovation impact in Beijing's cold climate zone.

## 2. Materials and Methods

Due to farmers' living habits and other special national conditions such as the basic economic conditions in rural China, the special heating forms in rural areas are determined. Particularly in the northern rural heating areas, the use frequency of different rooms of rural houses in winter, the demand for an indoor thermal environment and other related aspects are very different from those of Chinese cities and towns. There are mainly three living modes. Firstly, the economic conditions are good, the family has a large population and there are elderly people or children in the family for a long time. The requirements for indoor heating are stable, which is called "full time and full space mode", accounting for about 10%; secondly, the building area is large, the permanent population is small, some rooms are idle, and the heating demand is high, which is called "full time and part space mode", accounting for about 30%; thirdly, the resident population is lower and only needs heating in some use periods of common rooms. The heating demand is general, which is called "part time and part space mode"; it has the highest proportion, accounting for about 60%. Therefore, in the insulation of the building envelope, it is necessary to take a technical route suitable for specific characteristics. Restricted by the economic level of rural areas, the large-scale energy-saving renovation of the existing rural buildings envelope in rural areas needs to focus on the promotion of economic thermal insulation technology, such as by prioritizing the renovation of common rooms and the targeted thermal insulation transformation of the north-facing exterior wall, roof, exterior window, exterior door, etc., with the large heat loss in common rooms.

This article introduced Beijing's experience of energy saving renovations in rural buildings, which adopts a comprehensive research approach for district-level surveying, household surveying, field testing and energy consumption simulation. After verification, demonstration projects in the other rural communities in the same cold climate zone were carried out using the step-by-step approach to scaling up implementation. For more information on climate zoning, see reference [21], and some institutions can investigate the impact of improving energy efficiency in rural buildings.

### *2.1. Large-Scale Energy Saving Renovation of Rural Buildings in Beijing*

#### 2.1.1. District-Level Survey

Surveys of each district in Beijing are conducted through symposiums. Specifically, the relevant personnel from the district Housing and Construction Committee, New Rural Construction Office and township and county-level administrators are interviewed for the overall results of the initiatives and programs, while historical documents, such as the working guidebooks and household profiles from previous years, are collected as references. The district Housing and Construction Committee organizes a survey meeting for the village managers to coordinate and understand the basic situation of different villages and energy-saving measures, shown as Figure 2a.

The survey covers all ten districts (CP, DX, TZ, SY, FS, MTG, PG, HR, MY, YQ) of Beijing that have carried out large-scale anti-seismic and energy-saving renovation of rural houses; in particular, the survey reviews the amount and allocation process of the city/district incentive funds for single energy-saving renovation, new construction and comprehensive renovation; target household selection and renovation methods; determination of construction/supervision/appraisal organizations; the procurement, sampling inspection and acceptance plans of renovation materials; and other general opinions and suggestions.

(**a**) (**b**) (**c**)

**Figure 2.** On-site survey: (**a**) government symposium; (**b**) household Survey; (**c**) rural house after retrofit.

### 2.1.2. Household Survey

The survey mainly covers the rural residences under anti-seismic and energy-saving renovation from 2011 to 2015 as the overall sample database. These residences are recorded in the "Beijing Information System for the Management of Newly Built and Renovated Rural Housing Archive" (hereafter referred to as the Information System of Management), shown as Figure 2b,c. The survey content includes the basic situation of the residing rural households, information of the residence, the original anti-seismic and energy-saving measures, reinforcement and reconstruction, consumption of various types of energy and indoor environment conditions, etc., among which rural energy consumption refers to energy consumption in daily life (heating, cooking, water heating, air conditioning, lighting, household appliances, etc.) in rural areas. The energy consumed is mostly generated from biomass (straw and firewood) or commercial sources (coal, electricity, liquefied petroleum gas and natural gas).

According to the Information System of Management, the total number of rural households under anti-seismic and energy-saving renovation in Beijing during the "Twelfth Five-Year Plan" period is about 580,000, among which 2~3‰, or approximately 1200 households, are taken as samples. The number of survey samples in each district is determined according to the proportion of the number of households that completed renovation in each district to the city's renovation volume; 20 to 30 typical households are selected in each village; accordingly, 52 villages are set to be surveyed. Then, samples are randomly selected from the list of administrative villages in the city, ensuring sampled administrative villages are distributed in different townships so as to cover more rural households in different conditions. The samples selected are shown in Table 1. Before the household survey, all personnel involved are professionally trained regarding the survey content, methods and tasks.

**Table 1.** The proportion of renovate households in different areas and survey samples of households and villages.

| Survey District | DX | TZ | SY | FS | MTG | PG | HR | MY | YQ | CP | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Ratio | 12.6% | 15.6% | 17.4% | 12.6% | 0.7% | 10.9% | 5.2% | 8.9% | 7.7% | 8.3% | 100% |
| Sampled household No. | 150 | 180 | 200 | 150 | 40 | 130 | 60 | 100 | 90 | 100 | 1200 |
| Sampled villages No. | 5 | 6 | 8 | 8 | 7 | 2 | 5 | 3 | 5 | 3 | 52 |

#### 2.1.3. Field Test

To acquire thorough knowledge of the actual energy-saving renovation effect of rural buildings, the authors' team conducted field tests according to renovation arrangement in 2007, 2008, 2013 and 2017 on the heat transfer coefficient and winter energy consumption of some rural building envelopes that had undergone energy-saving renovation in the FS District, MTG District, HR District, DX District and MY District of Beijing. The test equipment used has been regularly inspected by the laboratory. The test contents include: (1) using a temperature self-recording instrument to continuously test the indoor temperature of selected typical rural buildings in the heating season, and obtain the hour-by-hour temperature of each main room to evaluate the indoor thermal comfort; (2) testing the heat transfer coefficient of different envelopes of typical rural buildings in the days of January (the coldest month) according to the requirements of relevant national standards; (3) using the tracer gas attenuation method to measure the cold air infiltration coefficient in the rooms. More details are introduced in the results section.

#### 2.1.4. Simulation of Energy Consumption

In this article, the toolkit DeST-h (Designer's Simulation Toolkits) software is used to simulate the energy-saving effect of rural buildings. The heat transfer coefficient tested was considered as the input parameter for simulation model. The basic algorithm is developed based on the state-space method, which was proposed by Tsinghua University in the early 1980s to analyze the thermal condition of buildings [22].

By analyzing field survey results, the rural buildings in Beijing are classified into five typical categories. The simulation analysis is carried out on the five actual insulation measures chosen by the rural households, i.e., no renovation; north wall insulation; north wall insulation + windows and doors renovation; north, east and west walls insulation; and north, east and west walls insulation + windows and doors renovation. The corresponding energy consumption and energy-saving rates of each measure are obtained.

#### 2.1.5. Estimation of Pollutant Emission Reduction

Chinese Standard for Building Carbon Emission Calculation (GB/T 51366-2019) is referred for calculation of the operational carbon emission of buildings [23,24]. The total energy consumption of each type in rural Beijing could be estimated by multiplying the average energy consumption per household and the number of households living in the rural areas, and the energy saving per household can be obtained through field test and simulation analysis.

Annual emission amounts of $PM_{2.5}$, CO, $CO_2$, NOx and $SO_2$ from solid fuels in rural Beijing were estimated based on the consumption of solid fuels and pollutant emission factors, which could be determined by the above measurement and field survey. A Monte Carlo simulation was repeated 10,000 times by MATLAB (The MathWorks, Inc., Natick, MA, USA) for emission amounts of different solid fuels in Beijing, and a 95%confidence interval (95% CI) was adopted to show the statistical data. The calculations of annual pollutant emission amounts were presented as follows (Formulas (1) and (2)) [25]:

$$E_{p,i,j} = G_{F,j} \cdot EF_{p,i,j} \times 10^{-6} \quad (1)$$

where i represents the pollutant species, corresponding to $PM_{2.5}$, CO, $CO_2$, $NO_x$ or $SO_2$, j is the solid fuel type, $E_{P,i,j}$ is the annual emission amount of pollutant "i" from solid fuel "j", in Gg, $G_{F,j}$ is the consumption of solid fuel "j" in tons and $E_{p,I,j}$ is the emission factor of pollutanti" from solid fuel "j" in g/kg.

$$E_{p,i} = \sum_{1}^{j} E_{p,i,j} \quad (2)$$

where $E_{P,i}$ is the annual emission amount of pollutant "i" from the corresponding solid fuel in the study.

*2.2. Implication to Other Cities in Same Zone*

As mentioned above, China begun to promote renovating existing buildings since 2017 in"2 + 26" cities, including Beijing, Tianjin, eight cities in Hebei Province, four cities in Shanxi Province, seven cities in Shandong Province and seven cities in Henan Province [8]. Whether the energy-saving renovation of rural building envelopes in other heating areas in similar climate zone can learn from Beijing's experience needs further analysis, verification and optimization according to local characteristics so as to form an implementation plan more suitable for those areas.

This article selects HZ city in Shandong Province, which is also in the cold region, to carry out the promotion application and effect tracking. HZ City now governs 2 districts and 7 counties, as well as the Economic Development Zone and High-tech Zone. The residential buildings in rural areas of the city are about 70–80% single-story rural houses, and about 20–30% two-story and multi-story rural houses. The basic situation of the rural houses before the renovation is as follows: the exterior wall is brick wall with 240 mm thickness, and the exterior wall finishes are mostly paint, without thermal insulation; the outer window is a single-layer wooden window; the outer door is a single-layer wooden door; the roof is mainly pitched roof without external insulation.

The specific strategy is to investigate the basic situation of the rural area before the transformation, conduct an on-site test on the thermal performance of the external wall before the transformation, and conduct on-site investigation on the roof and doors and windows. According to the testing and investigation results, the specific transformation scheme is given. After the implementation of the energy-saving transformation, the heat transfer coefficient of the transformation site was tested again on the spot. Combined with the testing data, the building energy consumption simulation software DeST-h modeling calculation was used to evaluate and analyze the comprehensive energy efficiency improvement rate of the building after the energy-saving transformation of the rural house.

## 3. Technical Measures of Energy-Saving Renovation

According to the characteristics of local rural buildings, different technical measures are formulated from three aspects: single insulation energy saving renovation; anti-seismic and energy-saving comprehensive renovation; and new construction and renovation.

*3.1. Single Insulation Energy Saving Renovation*

This measure is to renovate the exterior wall of rural buildings for external insulation and change external doors and windows for energy saving and insulation. To adopt this measure, the rural buildings should not be located in the reserved villages that are listed in the government reservation village plan, nor in those with demolition planned in the next five years, but should be intact and safe for living as is required and meet the seismic requirements.

*3.2. Anti-Seismic and Energy-Saving Comprehensive Renovation*

This measure refers to the anti-seismic strengthening of rural building structures and the energy-saving and insulation renovation of building envelopes, mainly targeted at the rural buildings that were built after 2005 in the planned reserved villages with basically intact seismic structures.

*3.3. New Construction and Renovation*

This measure is for the rural buildings newly built or rebuilt at the original site. To adopt this measure, the rural buildings should be single-story or multi-story houses built for own use on collectively owned rural land by using funds raised by the farmers of the village or members of the village's collective economic organizations and should pass all the required approval formalities. In addition, these buildings should meet the local design requirements for energy-saving building envelopes and comply with the seismic requirements.

## 4. Results and Discussion

### 4.1. Basic Situation in Beijing

#### 4.1.1. Energy-Saving Renovation Technical Measures

Beijing's rural buildings are mainly single-story, with the highest proportion beingsingle-story pitched roof building, accounting for 75%, and single-story flat roof building accounting for 22%. There are a few two-story buildings and other forms of housing. The average building area of rural houses is about 106.5 square meters, and the average heating area is about 97.8 square meters. Of the walls, 91% are solid brick with 240 mm thickness; 8% are hollow brick.

Rural buildings in Beijing should meet the design requirements (reduce 65% energy consumption) for energy-saving building envelope as specified in the Beijing's standard DBJ 11-602-2006.

In the energy-saving renovation of rural buildings in Beijing, external wall insulation is widely used in the wall insulation renovation of existing rural buildings. The external walls renovated were mainly north longitudinal walls and the east and west gables of the main house. The policy documents issued by the municipal government of Beijing require that the heat transfer coefficient (U-factor) of external walls should not be greater than 0.45 W/(m$^2$·K), the wall insulation materials to be used in each district should mainly use expanded polystyrene board (EPS) and extruded polystyrene board (XPS). The policy documents specify the type and thickness (greater than or equal to 50 mm) of the insulation board and the required fire protection rating (mainly B1 level). The specific measures should be implemented as needed by the enterprises tendered by the township government. In each district, most of the renovation schemes for the external doors and windows of existing rural buildings replaced them with hollow double-layer glass mainly composed of plastic steel and bridge-cut-off aluminum alloy. Table 2 shows the technical scheme of energy-saving renovation of building envelopes in each district of Beijing.

**Table 2.** Energy-saving renovation technical solutions for walls and windows in Beijing.

| District | Insulation Material | Thickness | Window Type |
|---|---|---|---|
| 1 | EPS | 80 mm | Plastic steel/bridge-cut aluminum alloy hollow double glass |
| 2 | EPS | ≥50 mm | Plastic steel/bridge-cut aluminum alloy/ordinary aluminum alloy hollow double glass |
| 3 | XPS | ≥50 mm | Plastic steel/bridge-cut aluminum alloy hollow double glass |
| 4 | XPS | ≥50 mm | Plastic steel/bridge-cut aluminum alloy hollow double glass |
| 5 | EPS | 70 mm | Plastic steel/bridge-cut aluminum alloy/ordinary aluminum alloy hollow double glass |
| 6 | EPS, XPS | 60~80 mm | Plastic steel/bridge-cut aluminum alloy hollow double glass |
| 7 | EPS | 70 mm | Plastic steel/bridge-cut aluminum alloy hollow double glass |
| 8 | EPS, XPS | 60 mm | Plastic steel/bridge-cut aluminum alloy hollow double glass |
| 9 | EPS | ≥70 mm | Plastic steel/bridge-cut aluminum alloy hollow double glass |
| 10 | XPS | 60 mm | Plastic steel/bridge-cut aluminum alloy hollow double glass |

#### 4.1.2. Indoor Thermal Comfort

Energy-saving renovation can significantly improve the indoor thermal environment and increase the indoor temperature in the heating season. The household survey shows that the expected indoor temperature of farmers in winter is 19.9 °C. The average room temperatures of rural houses before and after energy-saving renovation are 15.3 °C and 17.8 °C, respectively, with an average increase of 2.6 °C, which is close to the expected value. We usually carried out the survey and test more than one year after the completion of the renovation. Since 2016, Beijing has uniformly carried out the work of "coal to clean energy". After changing coal into clean energy, the average indoor heating temperature in rural houses is 17.9 °C, which is almost the same as that after the energy-saving renovation.

#### 4.1.3. Rural Household Satisfaction

The total proportion of farmers who are satisfied and very satisfied with the operation process, construction quality, energy-saving effect and self-financing expenses is over 80%, while the proportion of dissatisfied farmers is below 10%, of which the dissatisfaction rates of the operation process, energy-saving effect and self-financing expenses are only 1%, 2% and 3%, respectively.

#### 4.1.4. Energy Consumption for Heating in Winter

From 2008 to the end of 2016, 710,000 rural renovations have been carried out in Beijing. In order to quantitatively calculate the average energy-saving rate of thermal insulation renovation of rural buildings in Beijing, estimation and then weighted summation is adopted for rural buildings that used the three technical measures of energy-saving renovation (single insulation energy saving renovation; anti-seismic and energy-saving comprehensive renovation; new construction and renovation). According to the statistics of the Information System of Management, the percentages of rural households in the single renovation, new construction and renovation and comprehensive renovation in Beijing are 72%, 21%, and 7%, respectively.

The proportions of different renovation technical schemes (including four situations: north wall thermal insulation; north, east and west walls thermal insulation; north wall thermal insulation + door and window renovation; north, east and west walls + door and window renovation) are obtained by survey statistics, and the energy-saving rate is obtained by simulation calculation in Section 2.1.4, as shown in Table 3.

**Table 3.** Ratio and energy saving rate of different energy saving renovation technical solutions in Beijing.

| Type | Renovation Type | Renovation Ratio | Simulation Value of Energy Saving Rate |
|---|---|---|---|
| Single renovation | North wall | 7% | 12% |
| | North, east and west walls | 5% | 19% |
| | North wall, door and window renovation | 36% | 26% |
| | North, east and west walls, door and window renovation | 53% | 31% |
| New construction and renovation | North wall | 1% | 12% |
| | North, east and west walls | 1% | 19% |
| | North wall, door and window renovation | 18% | 26% |
| | North, east and west walls, door and window renovation | 81% | 31% |
| Comprehensive renovation | North wall | 2% | 12% |
| | North, east and west walls | 3% | 19% |
| | North wall, door and window renovation | 16% | 26% |
| | North, east and west walls, door and window renovation | 80% | 31% |

Therefore, it can be calculated that the average energy-saving rate of the thermal insulation renovation of rural buildings in Beijing is about 30.0%. According to the results of a household survey [26] on more than 4000 households in Beijing in 2013, the heating energy consumption in Beijing's rural areas in 2012 was 4.42 million tons of standard coal. Combined with the above-mentioned average energy-saving rate of rural house insulation renovation, we can calculate that if 2012 is the base year of energy consumption, Beijing can achieve the annual energy conservation of 590,000 tons of standard coal by the end of 2016 after the insulation renovation work of 710,000 rural houses. In the future, after Beijing has completed the energy-saving renovation of all 1.495 million rural households, the total annual energy conservation can reach 1.25 million tons of standard coal, which is equivalent to the total coal consumption of a 600,000 kW power generator at full load throughout the year.

#### 4.1.5. Estimation of Pollutant Emission Reduction

According to the test and statistical results, the amount of $PM_{2.5}$ and various gaseous pollutants emitted from solid fuels, such as scattered coal, briquette and honeycomb briquette used for rustic heating in rural Beijing in 2012 [25], as well as the reduction of pollutants brought about by energy conservation through the thermal insulation renovation of the building envelope, are shown in Table 4.

**Table 4.** Baseline and reduction of pollutant emissions from rural heating in Beijing.

| Pollutant Type | $PM_{2.5}$ (Ton) | CO (Ton) | $CO_2$ (Million Ton) | $SO_2$ (Ton) | NOx (Ton) |
|---|---|---|---|---|---|
| Baseline emissions | 17,900 | 323,000 | 12.74 | 6900 | 11,000 |
| Current emission reduction amount | 2400 | 43,000 | 1.70 | 900 | 1500 |
| Total emission reduction amount for future | 5000 | 91,500 | 3.60 | 2000 | 3100 |

It can be seen from Table 4 that if 2012 is taken as the base year of emission, Beijing can achieve an annual reduction of 2400 tons of $PM_{2.5}$ emissions, 43,000 tons of CO emissions, 1,700,000 tons of $CO_2$ emissions, 900 tons of $SO_2$ emissions and 1500 tons of NOx emissions by the end of 2016 after the thermal insulation renovation of 710,000 rural houses. In the future, after completing the energy-saving renovation of 1,495,000 rural households in Beijing, about 5000 tons of PM2.5 emissions, 91,500 tons of CO emissions, 3,600,000 tons of $CO_2$ emissions, 2000 tons of $SO_2$ emissions and 3100 tons of NOx emissions can be reduced every year.

### *4.2. Implication to Other Cities in Same Zone*

As mentioned before, this article selects HZ city in Shandong Province to carry out the promotion application and effect tracking. The current situation of HZ city is mainly similar to that of Beijing. Meanwhile, there are many thermal insulation materials in the construction market presently, such as EPS and XPS mentioned above, as well as polyurethane board, rock wool board, vacuum insulation board, etc. However, the application of other types of thermal insulation materials on demonstration projects is limited in rural building energy efficiency renovation compared to EPS and XPS. Therefore, this article gives the case of a city considering the local common thermal insulation material, EPS board.

According to the experience of Beijing, the specific transformation strategy for the rural areas of the city is as follows: the outer wall adopts the construction method of the external thermal insulation system of the 55 mm/60 mm thickness EPS board (thermal conductivity is lower than 0.042 W/(m·K)) thin plastered outer wall; when the outer wall does not meet the thermal insulation construction conditions, the construction method of the EPS thin plastered inner thermal insulation can be used locally, and the replacement of energy-saving doors and windows or the addition of the special thermal insulation sealing curtain for the outer doors and windows are also considered.

The testing scope and quantity of the evaluation work are determined according to the following principles: comprehensive coverage of the sort of transformation strategy; full coverage of typical rural housing types (shown as Figure 3); the number of rural houses covered by each transformation scheme shall not be less than 1‰ of the number of households modified by this scheme; the representative village will choose at least two main rural homes; surveying and testing was carried out more than one year after the completion of the renovation. Figure 4 displays images from a field test.

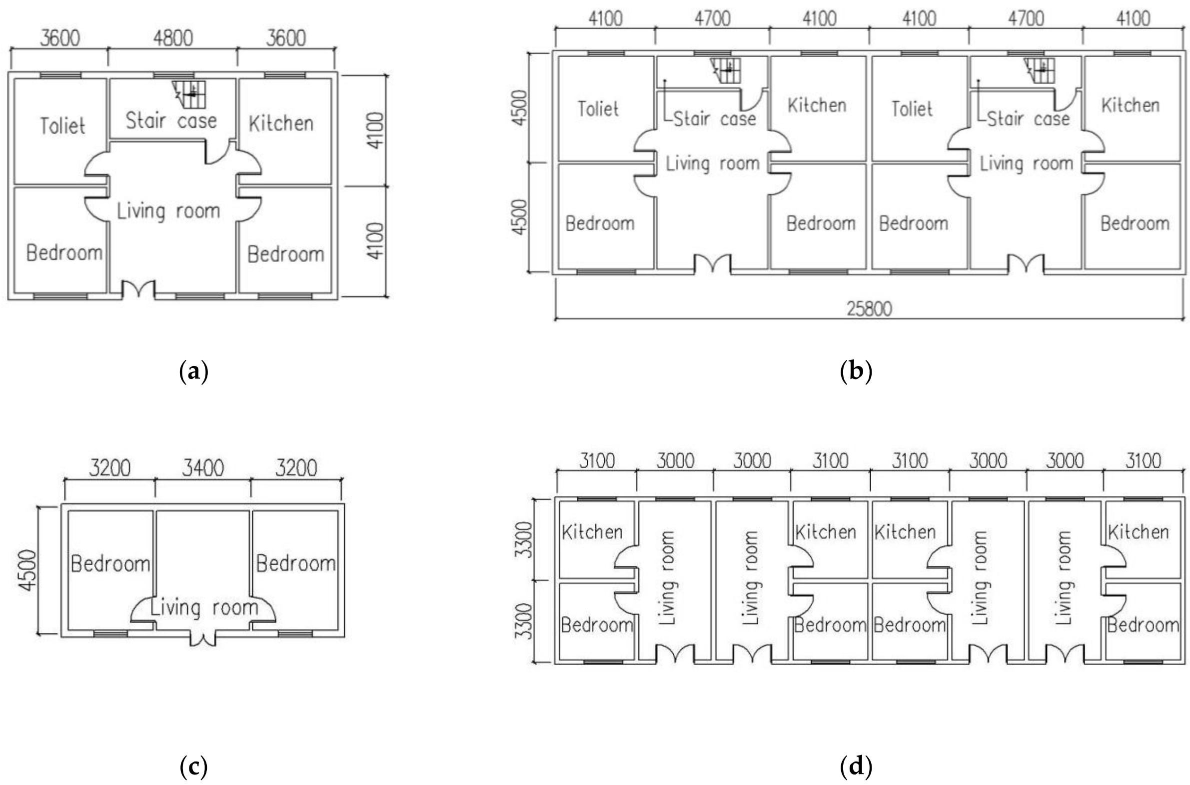


**Figure 3.** The architectural drawings of typical rural houses in mm: (**a**) two-story sloping roof rural house; (**b**) two-story flat roof rural house; (**c**) single-story sloping roof rural house; (**d**) two-story side-by-side building.

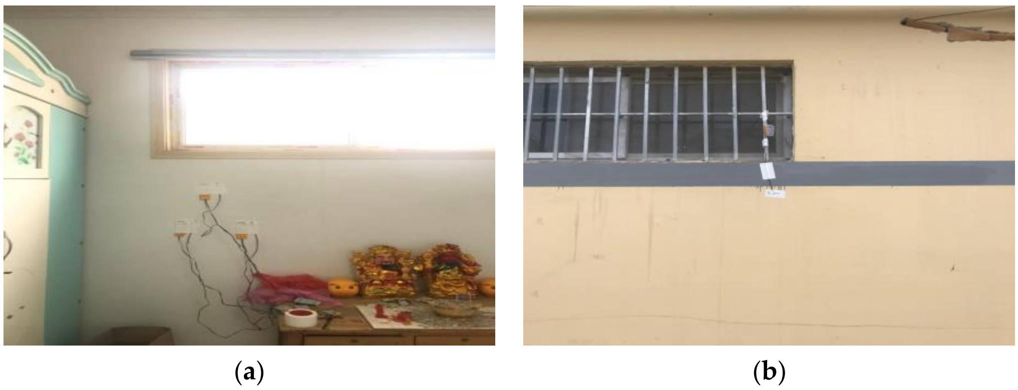


**Figure 4.** Field test photos: (**a**) interior surface of exterior wall; (**b**) exterior surface of exterior wall.

According to Table 5, the actual testing average value of the heat transfer coefficient (U-factor) of the exterior wall of typical rural houses before the transformation was 2.13 W/m$^2$·K; after reconstruction, the average heat transfer coefficient of the exterior wall was 0.60 W/m$^2$·K (EPS insulation with 55 mm thickness) and 0.56 W/m$^2$·K (EPS insulation with 60 mm thickness), respectively, and the reconstruction effect is obvious.

According to the field test, analysis and evaluation, the building energy efficiency improvement rate of single-story rural houses with the renovation of all exterior walls and all exterior windows, two-story townhouses with the renovation of first floor exterior walls and all exterior windows, and two-story townhouses with the renovation of all exterior walls and all exterior windows in rural areas of the city, is more than 30% (as shown in Table 6). The transformation cost is generally 80 RMB per square meter, i.e., about 8000 RMB per household.

**Table 5.** Actual test value of heat transfer coefficient of exterior wall of typical farmers.

| No. | Rural House | Heat Transfer Coefficient, $W/m^2 \cdot K$ Testing Value | Heat Transfer Coefficient, $W/m^2 \cdot K$ Average Value |
|---|---|---|---|
| 1 | House 1,two-story sloping roof rural house | 0.55 | 0.61 (EPS insulation with 55 mm thickness) |
| 2 | House 2, single-story sloping roof rural house | 0.60 | |
| 3 | House 3 and 4, two-story side-by-side building | 0.65 | |
| 4 | House 5, single-story sloping roof rural house | 0.64 | |
| 5 | House 6, two-story side-by-side building | 0.57 | 0.56 (EPS insulation with 60 mm thickness) |
| 6 | House 7, two-story side-by-side building | 0.54 | |
| 7 | House 8, before renovation for base line | 2.13 | 2.13 |
| 8 | House 9, before renovation for base line | 2.14 | |

**Table 6.** Energy efficiency improvement rate (EER) before and after renovation.

| No. | Rural House | Heat Consumption Index before Renovation | Heat Consumption Index after Renovation | EER(%) |
|---|---|---|---|---|
| 1 | House 1,two-story sloping roof rural house | 40.0 $W/m^2$ | 25.9 $W/m^2$ | 35.2% |
| 2 | House 2, single-story sloping roof rural house | 42.5 $W/m^2$ | 26.4 $W/m^2$ | 37.8% |
| 3 | House 3 and 4, two-story side-by-side building | 37.1 $W/m^2$ | 24.9 $W/m^2$ | 32.8% |
| 4 | House 5, single-story sloping roof rural house | 49.9 $W/m^2$ | 34.9 $W/m^2$ | 30.0% |
| 5 | House 6, two-story side-by-side building | 42.9 $W/m^2$ | 24.97 $W/m^2$ | 41.8% |
| 6 | House 7, two-story side-by-side building | 42.9 $W/m^2$ | 24.50 $W/m^2$ | 42.9% |
| | The average ratio | | | 36.8% |

With the proposal of China's 2030 carbon peak and 2060 carbon neutral goals, the energy efficiency work of rural buildings will gradually deepen, and the energy renovation of rural housing envelope will become one of the important works. Specific economical thermal insulation transformation scheme of enclosure structure should be given for rural houses in different regions, which can achieve the goal of an energy efficiency improvement rate of more than 30%; meanwhile, the initial investment of each household should basically not exceed 8000 RMB. Therefore, this article provides a strong reference for large-scale application and further promotion in the northern rural areas with the same climate zone.

## 5. Conclusions

Beijing has comprehensively promoted the energy-saving and thermal insulation renovation of rural residential buildings and successfully created the first "Beijing Model" on a large scale and systematically from the whole city level in China. It has accumulated a lot of experience in the technical scheme, management mechanism and promotion modes. Through government symposiums, field surveys, field measurements, simulation analysis and other research methods, the implementation scheme and policy system for energy-saving renovation of rural buildings in Beijing in the cold climate zone were sorted out, analyzed and evaluated. For the first time, the thermal insulation scheme for the exterior wall of the enclosure structure of the farmhouse was put forward, and the demonstration project was successfully implemented. This mode not only effectively and significantly reduces the heating energy consumption of rural houses in winter; it also makes farmers realize the importance and necessity of the energy-saving transformation of rural houses. The formation of this idea paved the way for the promotion of the energy-saving transformation of rural houses and other rural energy-saving technologies in other regions. The HZ city in Shandong Province with a similar climate zone was selected to carry out the promotion application and effect tracking. The following conclusions were drawn:

1. Beijing has established a long-term mechanism, with policy and demonstration as the guide, and investment as the guarantee. Regional implementation of the mechanism effectively promoted the rural housing anti-seismic and energy-saving livelihood projects. In the promoting process, Beijing has adopted a scientific and effective multi-

sectoral coordination, work linkage mechanism and management service system, which has strong reference significance;

2. The average energy-saving rate of the thermal insulation renovation of rural houses in Beijing is about 30.0%, and the average room temperature has increased by 2.6 °C after the renovation. The total proportion of farmers who are satisfied and very satisfied with the operation process, construction quality, energy-saving effect and self-financing expenses is over 80%, while the proportion of dissatisfied farmers is below 10%;
3. The large-scale energy-saving renovation of rural buildings promoted in Beijing can save millions of tons of standard coal and a large amount of pollutant emissions each year, achieving significant economic, environmental and social benefits;
4. The success of the energy-saving renovation of rural buildings in Beijing depends on the policy guidance and the relatively high economic level of Beijing;
5. Beijing's experience concerning the large-scale energy-saving renovation of rural building envelopes has further analysis, verification, and optimization in other similar climatic zones; The average energy-saving rate in the promoted cities can reach 30.0% and above. Therefore, this experience can be further promoted and implemented in more cities in cold climate zones, especially in "2 + 26" cities.

**Author Contributions:** Conceptualization, X.Y.; Methodology, M.S. and X.Y.; Validation, Q.D.; Investigation, Q.D., G.Z., S.Z. and Y.L.; Data curation, M.S., S.Z. and Y.L.; Writing—original draft, M.S.; Writing—review and editing, Q.D. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was funded by CABR Corporate Research Fund "Research on low carbon and carbon neutral design methods and key technologies of residential and public buildings" (No. 20220109330730005), Project of Ministry of Housing and Urban-Rural Development (2022-K-185) and Xuzhou Housing and Urban-Rural Development Bureau's project "Research Service on the Organizational System and Institutional System of Green Urban-Rural Development" (JSZC-320300-RJJS-C2022-0001001).

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** Not applicable.

**Conflicts of Interest:** The authors declare no conflict of interest.

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