The Reduction Potential of Energy Consumption, CO$_2$ Emissions and Cost of Existing Urban Residential Buildings in Hangzhou City, China

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Abstract

China has become the second largest emitter of CO$_2$ in the world. As one of the largest energy consumers, urban residential buildings are required to reduce energy consumption. However, nearly all existing urban residential buildings in the Hot Summer and Cold Winter Region of China were built with poor thermal quality. Increasing a building's energy performance has proven to be very helpful in alleviating the pressure of energy shortages and in reducing CO$_2$ emissions. After analyzing the climate of the region, the economic development and existing urban residential buildings of Hangzhou city, one typical building is selected as a case study. Six rational renovation plans, based upon the national and regional standards, are advanced after analyzing their feasibility in simulations and in practice. The energy saving effects of the plans are analyzed using the feedback coefficient method, the reduction of CO$_2$ emissions by a simple LCCO$_2$ method and the costs by a simple LCC method, all for a 40-year residual life span. Based upon these results a suitable plan is developed. The results show that the renovation of existing residential buildings, through the thermal insulation of their building envelopes, is very beneficial in reducing energy consumption and CO$_2$ emissions.

Keywords: CO$_2$ emission; existing residential buildings; renovation; feedback coefficient; LCCO$_2$; LCC; thermal insulation

1. Background and Introduction

The miraculous economic development in China has led to enormous increases in energy use. This energy use has caused the world to focus on China because it now accounts for the second largest amount of CO$_2$ emissions in the world after that of the United States. In response, the Chinese government has recently required urban residential buildings, one of the largest energy consumers, to reduce energy consumption. Adversely, Chinese cities are rapidly urbanizing and more energy is consumed to improve people's living conditions. To make matters worse, all existing urban residential buildings in China were built with poor thermal qualities. In the less amiable climatic environment of cities, greater energy consumption occurs in order to maintain a comfortable indoor environment for these residential buildings.

Increases in buildings' energy performances have proven to constitute an important instrument in the efforts to alleviate the pressures of energy shortages and CO$_2$ emissions. B. Poel et al. (2007) developed an energy performance assessment for existing dwellings in the framework of a European project. O. Arslan et al. (2006) showed that the insulation of external walls was very important and determined the optimum insulation thickness in existing buildings for Kutahya, Turkey based on thermo-economic analysis. H. Tommerup et al. (2006) illustrated how a profitable 80% savings potential of energy used for space heating could be identified over 45 years within the Danish residential building stock if the energy performances are upgraded through proper renovation. G. Verbeeck et al. (2005) showed that a decrease in energy consumption and greenhouse gas emissions would occur if residential buildings had improved insulation measures, better glazing, and renewable energy systems. A. Papadopoulos et al. (2002) showed that the improvement of prevailing indoor thermal comfort conditions and improvement of environmental conditions in Swedish urban areas could be achieved through energy renovation in existing buildings and that it is an important tool for the reduction of energy...
consumption in the building sector. Lollini et al. (2006) demonstrated the significant global benefits of well-insulated buildings based upon energy, economic and environmental factors. A. Hestnes et al. (2002) showed that it was possible to significantly reduce energy consumption in existing European office buildings by using passive and low energy technologies. T. Siller (2007) found that a reduction in total energy consumption and CO₂ emissions of the Swiss residential building stock could be reached by reducing the specific heat demands of existing buildings during renovation. M. Jakob (2006) concluded that thermal insulation measures in buildings with previously non-insulated building envelopes were, in most cases, profitable from an energy-economic point of view.

China is behind the world in this regard and will likely take advantage of the experience of developed countries for existing buildings. Experts and the government have been aware of the energy saving potential of urban existing residential buildings, and several national (2000) and regional (2006) standards were published to direct energy saving renovations of existing urban residential buildings in the Cold Region of China. S. Lang, (2004) described energy-efficiency specifications for the renovation of existing residential heating systems in Northern China. Z. Wang et al. (2004) stated that refurbishment of existing apartments had become very popular since 1990, and building energy-saving systems would be applicable to existing buildings in a wide range of climatic conditions.

This paper represents the first study on the reduction potential of energy consumption, as well as the reduction in CO₂ emissions and costs of urban residential buildings in the Hot Summer and Cold Winter Region of China. Although there have been no prior publications regarding this topic, the experiences of developed countries along with the standards and research done in Northern China provide helpful advice.

The region's first national energy saving standard was published in 2001 for the energy efficiency of new and rebuilt residential buildings (2001). Between 1978, when Economic Reform began, and 2001, a large number of residential buildings were erected and are now subject to future refurbishment due to a contaminative urban environment and the relatively poor protective systems in Chinese cities. As a result, a golden opportunity now exists to improve the energy performance of residential buildings through refurbishment. This paper attempts to identify the most effective renovation plans for these buildings by comparing the energy savings performance and CO₂ emissions reductions among the variables advanced by the standard. Additionally, a cost comparison of each plan will be made in order to make a compelling argument for their successful implementation.

2. Methodology
2.1 Research subject
2.1.1 Description of the Hot Summer and Cold Winter Region and Hangzhou city

The national energy saving standard of 2001 specifies that most eastern and western areas of China are part of the Hot Summer and Cold Winter Region. Y. Feng (2004) contended that residential buildings in this region must include both heat insulation (in summer) and heat preservation (in winter) thermal designs. If carried out, this will have a significant impact because the region, while representing less than 20% in area, accounts for more than 40% of the Chinese population and nearly 50% of the country's economy.

Fig.1. Climatic Regions in China, and Hangzhou City's Location

Hangzhou, the capital of Zhejiang Province, is a typical city in the region (See Fig.1.). It is located in the South Wing of the Yangtze River Delta. This happens to be the most developed economic region in China. The per capita GDP of the city grew more than three times that of China between 1996 and 2005. Not surprisingly, the energy shortage of the province has also been the most acute here and has seriously restricted economic development and normal residential life (2005). The Hangzhou statistical yearbook (2006) reported that urban residential electricity consumption increased from 986 kWh in 2000 to 2,798 million kWh in 2005. Although the governments of the province (2003) and the city (2002) have both published individual detailed energy-saving standards for new and rebuilt residential buildings, real estate developers are reluctant to comply with the codes due to increased costs and uncertain benefits for buyers. Additionally, buildings with large area windows, complicated shapes, etc. are very popular in the city's real estate market. As a result, the market is strongly against energy saving codes and at least 95% (e.g., 475 million m²) of residential buildings in the city have been designed and built without considering energy-saving measures and with poor thermal quality. In the next decade buildings constructed in the 1980s and 1990s will be refurbished with energy savings
taken into account (thereby adhering to the residential energy saving standards) before being demolished. It is therefore, necessary and meaningful to examine suitable plans for, and co-benefits from, energy saving renovations of existing urban residential structures in the city.

With the continually developing economic situation throughout the entire country, all other cities in this region will, in the foreseeable future, also experience the same problems as those that have occurred in Hangzhou. For this reason it is hoped that information presented in this paper will not only provide a general idea about the residential energy savings in the city, but also offer some solutions for future energy studies for other cities in the region and throughout the country as a whole.

2.1.2 Description of existing residential buildings in Hangzhou city

According to the Hangzhou statistical yearbook (2006), more than 250 million m$^2$ of residential buildings were built in the city prior to 2001. These buildings are now at least seven years old and becoming dilapidated. The solutions available are the demolition and construction of new ones, or the renovation of existing buildings.

Renovation (upgrading the condition) of existing buildings should be a priority as it offers an opportunity to take cost-effective measures to transform the residential structures into resource efficient and environmentally sound buildings. Equally important is the fact that renovation costs are significantly lower than demolition and reconstruction (N. Kohler, 1999). Additionally, in light of sustainability principles and policies, it makes sense to renovate the old buildings rather than demolish them and build new ones.

This paper uses a seven-story building (See Fig.2.) built in 1995 in the Zijin neighborhood of the city as a typical building in the case study in order to estimate the savings potential. The building is chosen as it represents 51.9% of the type of residential buildings built before 2001 and will have to be renovated in the near future. It holds particular value in helping to determine suitable plans for energy savings while increasing social and financial values. The residential building has 28 households and there are no vacancies.

| Table 1. List of Variables for the Energy Saving Renovation Plans |
|---------------------------------------------------------------|
| **Variable**                                      | **Effect on energy** |
|                                               | **consumption** | **Feasibility in** | **Feasibility in** | **Selected or** | **Reason** |
|                                               | **simulation** | **practice** |                                    | not**     |     |
| Buildings layout in the Zijin neighborhood      | High           | Low          | Low               | Not        | A, C |
| Orientation of the subject building             | High           | High         | Low               | Not        | A   |
| Shape coefficient/Closed or open stairs         | High           | High         | Medium            | Yes        |     |
| The ratio of exterior windows/wall area         | High           | Low          | Low               | Not        | A   |
| K (heat transmission coefficient) of exterior   | High           | High         | Medium            | Yes        |     |
| windows                                        |                |              |                   |            |     |
| Shadow coefficient of exterior windows          | High           | High         | High              | Yes        |     |
| Airproof degree of exterior windows             | High           | Low          | High              | Not        | C   |
| K and D (i.e. thermal inertia index) of roof    | High           | High         | Medium            | Yes        |     |
| K and D of exterior wall                        | High           | High         | Medium            | Yes        |     |
| K of partition wall                             | Low            | High         | Medium            | Not        | B   |
| K of exterior door                              | Low            | High         | High              | Not        | B   |
| K of floor board                                | Low            | High         | Medium            | Not        | B   |
| K of ground floor board                         | Low            | High         | Medium            | Not        | B   |
| Absorption coefficient of roof and exterior wall| High           | High         | Medium            | Yes        |     |
| surface                                        |                |              |                   |            |     |
| Green vegetation planted on exterior wall and   | High           | Low          | Medium            | Not        | C   |
| roof                                          |                |              |                   |            |     |

Reason: (A) Cannot be changed optionally in practice and/or simulation. (B) Very little effect on energy consumption though listed in the energy saving standards, and (C) Very difficult to quantifiably analyze the effect on energy consumption in simulation.
18°C in winter), (4) setting air change rate (one time per hour), and (5) inputting a typical year's weather for Hangzhou city.

2.2.2 Variables of building's thermal attributes

There are many variables that affect residential energy consumption. In the national and regional standards for residential energy savings, better energy saving design is expected to decrease energy consumption for space heating and cooling by 30% and more effective equipment is expected to decrease that by 20%. A variety of reusable energies, especially solar energy and underground thermal energy are also being encouraged to supplement a portion of the general energy supplies in residential buildings. In this paper, fifteen variables belonging to the building energy saving design will be selected to examine their viability for successful renovation plans. Of these, several will be excluded later for reasons listed in Table 1. The remaining variables will be related to improving the upgrading of the subject building in the renovation plans.

2.2.3 Thermal attributes of the subject building

When the subject building was designed and built, the standard for the building envelope was set based on the common practice at the time. In order to meet the target and produce feasible plans for the subject building's energy saving renovations that comply with the new correlative standards, it is necessary to clarify all actual information concerning the building's attributes, particularly in regards to the thermal aspect.

The following is a description of the subject building's thermal variables that will be improved in the study.

1. Since the stairs are not enclosed, air is directly exchanged with the outdoors. The resulting shape coefficient is 0.38.

2. The ratio of exterior windows/wall area is shown in Table 2. The K (heat transmission coefficient) and SC (shadow coefficient) of exterior windows (aluminum frame and 5mm glass) are 6.25 W/(m²·k) and 0.80.

3. The K and D (thermal inertia index) of the roof are 3.969 W/(m²·k) and 1.554 respectively.

4. The mean K and D of the exterior walls are 2.355 W/(m²·k) and 3.251.

5. The absorption coefficient of the roof and exterior walls' are 0.60 and 0.70.

2.2.4 Energy saving renovation plans and thermal calculation model

Six rational renovation plans are suggested following further analysis of the variables and the subject building's thermal attributes, shown in Table 3.

Plan 0: The energy consumption of subject building is calculated as a benchmark in order to measure the energy savings of the following renovation plans.

| Plan | Measures |
|------|----------|
| 0    | No change and used as a benchmark |
| 1    | Closing stairs by installing building doors and windows to separate the stairs from the outside air |
| 2    | Substituting plastic double windows for old ones |
| 3    | Applying unfixable curtains or blinds to reduce exterior windows' SC in summer |
| 4    | Adding insulation material (40mm Extruded Polystyrene (XPS)) onto roof. |
| 5    | Adding insulation material (10mm Extruded Polystyrene (XPS)) onto exterior walls |
| 6    | Applying light colored paint to outside surfaces of the envelope to alter the absorption coefficient |

Plan 1: Installing two safety doors (the building's doors, not families' doors), on the first floor and twelve windows on the remaining six floors, thereby separating the stairs from the outside air, changes in the shape coefficient of the building to 0.32. The ratio of exterior windows/wall area, illustrated in Table 4., will also change. The K and D of the exterior walls changes to 2.405 W/(m²·k) and 3.191 respectively. The new K of the exterior door will be 6.5 W/(m²·k) because the stairs' two safety doors are steel. All other parameters are the same as those of the subject building.

Plan 2: Substituting plastic double windows for old ones. The K and SC of the exterior windows change to 2.85 W/(m²·k) and 0.70. All other parameters are the same as those of the subject building.

Plan 3: Applying unfixable fabric, timber curtains and/or aluminum blinds reduces the SC of the exterior windows to 0.30 in summer. Other parameters not mentioned here are the same as those of the subject building.

Plan 4: Adding insulation material (40mm XPS) to the roof changes the roof's K and D to 0.672 W/(m²·k) and 2.376. All other parameters are the same as those of the subject building.

Plan 5: Adding insulation material (10mm XPS) to the exterior walls will change the K and D to 1.296 W/(m²·k) and 3.236. All other parameters are the same as those of the subject building.

Plan 6: Applying light colored paint to the surface of the exterior walls and roof changes the absorption coefficient of the outside surface to 0.4. All other parameters are the same as those of the subject building.

3. Results and Discussion

3.1 Analysis of energy saving effect

The energy consumption for space heating and cooling of the six plans is calculated through use of the evaluation program Doe-2 (shown in Table 5.). In
order to compare the energy savings effect of the above plans, energy consumption of the subject building is used as a benchmark.

Table 5. The Thermal Calculation Results

| Plan | Energy consumption (kWh/yr) | kWh/(m²·yr) | Reduction ratio |
|------|-----------------------------|------------|----------------|
| 0    | 225,737                     | 90.79      | -              |
| 1    | 215,932                     | 86.85      | -4.34%         |
| 2    | 196,411                     | 78.99      | -12.99%        |
| 3    | 210,697                     | 84.74      | -6.66%         |
| 4    | 196,429                     | 79.00      | -12.98%        |
| 5    | 197,125                     | 79.28      | -12.67%        |
| 6    | 221,256                     | 88.98      | -1.99%         |

The results of each plan’s evaluation show great differences among the six plans in terms of energy savings. The following revelations are found:

(1) The largest energy saving potential can be achieved by upgrading the insulation performance of the existing buildings’ envelope. Because the windows, roof and exterior walls constitute the three main parts of the subject buildings’ envelope, the most significant reduction in total energy consumption can be achieved by Plans 2, 4, and 5.

(2) By comparing Plans 2 and 4 with Plan 5 we show that the greatest potential to reduce energy consumption is achieved by upgrading the weakest part in thermal performance.

(3) Repainting of the outside surface of exterior walls and the roof should be implemented to improve the summer indoor environment despite the fact that it would have the smallest positive effect because such repainting cannot be avoided when renovating (i.e. Plan 4, 5).

(4) In Chinese cities, occupants like using unfixable fabric or timber curtains indoors and near windows, occasionally installing fixable fuscous awnings for outdoor and elevated windows. Although the SC of these traditional shielding methods cannot be easily determined, the effect cannot be ignored. As a result, Plan 3 should be encouraged as widely and uniformly as possible.

(5) Besides reducing energy consumption, the enclosing of stairs can also provide occupants with a transition space to adapt to the change between comfortable indoor and uncomfortable outdoor environments when entering or leaving. After weighing the effects on reducing CO₂ emissions and costs, it will be decided whether Plan 1 will be applied or not.

(6) No one single plan can attain the target (50% energy savings for space heating and cooling) by itself where the energy consumption for space heating and cooling are 30.00, and 26.40 kWh/(m²·yr) respectively and the resulting annual total is 56.40 kWh/(m²·yr). Therefore several plans should be combined in order to comply with the standards.

3.2 Analysis of CO₂ emission reduction

Increased energy consumption will lead to environmental problems, the most important of which is global warming. According to Dincer (1999) (Dincer et al., 1999), CO₂ emissions contribute to nearly 50% of the global warming problem.

In general, building-related energy-saving measures reduce energy consumption and thereby significantly reduce CO₂ emissions. But it is often debated that the reduction in energy use does not necessarily lead to benefits for the environment, due to production, transportation and decommissioning costs. A simple life cycle analysis (LCCO₂ method) can be carried out to determine the environmental impact of the six plans mentioned in this study. As a result, this paper, apart from reducing CO₂ emissions during the operational phase of the subject building, also takes into account the initial embodied CO₂ emissions.

Table 6. The Conversion Factors (*Recycling was considered)

| Energy/Material | Unit | CO₂ emission [kg/Unit] |
|-----------------|------|------------------------|
| Electricity     | kWh  | 0.95                   |
| Glass           | kg   | 1.40                   |
| PVC profile     | kg   | 8.69                   |
| Section steel*  | kg   | 1.40                   |
| Concrete        | kg   | 0.19                   |
| Steel bar*      | kg   | 0.92                   |
| Polystyrene     | kg   | 17.25                   |
| Aluminum*       | kg   | 1.02                   |
| Timber          | kg   | 0.2                    |
| Paint           | kg   | 1.63                   |

The CO₂ emissions from electricity production and materials in China in the plans are shown in Table 6. (cited in Zhao et al., 2004, Gong et al., 2004, Chen et al., 2004, Liu, 2002). The datum concerning paint is revised from the Japanese database (2003).

Since the design code (1999) regulates that residential buildings be designed to operate for at least 50 years, the residual period of the subject building's life cycle is expected to be 40 years after the present renovation discussed in the paper. And some innovation plans/measures, whose life spans are less than 40 years, will have to be implemented more than once during the 40 years.

Eventually the subject building will be demolished, despite being renovated or not and the resulting CO₂ emissions from demolition will be equivalent to or less than present if technological advances in the future are taken into account. Additionally, the possible recycling of materials has been considered in the conversion factors. Therefore, assumptions on the buildings destiny after 40 years have not been made and the end phase of the building is not incorporated in the simple LCCO₂ method used in the paper.

The final CO₂ emission of the plans will be calculated as follows: Multiplying the annual reduction of CO₂ emission for electricity saving by 40 years, and subtracting the initial embodied CO₂ emission produced in renovations. The results are shown in Table 7.

In comparison to the final reduction of CO₂ emissions, the initial embodied CO₂ emissions for renovations is so small that it can be overlooked. As a result, all six of the plans discussed in this paper...
Table 7. Final Reduction of CO₂ Emission in Next 40 Years

| Plan | Initial embodied CO₂ emission [kg] | Reduction of CO₂ emission [kg/yr] | Duration [yr] | Renovation times | The final reduction of CO₂ emission [kg] |
|------|-----------------------------------|-----------------------------------|--------------|-----------------|----------------------------------------|
| 1    | 4,639.57                          | 9,314.36                          | 20           | 2               | 363,295                                |
| 2    | 68,159.76                         | 27,859.05                         | 20           | 2               | 978,042                                |
| 3    | 91.56–9,339.12                    | 14,287.21                         | 10/20        | 4/2             | 571,122/552,810                        |
| 4    | 15,115.66                         | 27,842.17                         | 40           | 1               | 1,098,571/14                          |
| 5    | 14,698.03                         | 27,810.79                         | 20           | 2               | 1,083,035/54                          |
| 6    | 1,463.08                          | 4,275.36                          | 10           | 4               | 165,162                                |

Table 8. Final Reduction of Cost in Next 40 Years

| Plan | Initial cost [¥] | Energy saving [¥/yr] | Duration year [yr] | Pay back year [yr] | Renovation times | Final reduction of cost [¥] |
|------|------------------|----------------------|--------------------|-------------------|-----------------|--------------------------|
| 1    | 20,000           | 5,195.43             | 20                 | 3.85              | 2               | 167,737                  |
| 2    | 140,000          | 15,542.42            | 20                 | 9.01              | 2               | 341,696                  |
| 3    | 22,890–141,918   | 7,079.76             | 10/20              | 3.23/20.05        | 4/2             | 191,630/464             |
| 4    | 84,810           | 15,533.00            | 40                 | 5.46              | 1               | 536,510                  |
| 5    | 180,000          | 15,162.02            | 20                 | 11.87             | 2               | 246,480                  |
| 6    | 75,537           | 2,385.20             | 10                 | 31.67             | 4               | -206,740                 |

can be considered beneficial and promising from an environmental point of view.

3.3 Analysis of cost reduction

It is easy to understand the energy and environmental benefits that can result. However, the economic costs are critical, as tenants see them as an undesirable addition to the dwelling at the purchase phase, and additionally pay little attention to future managing costs. To compound matters, the financial savings for energy saving measures on existing buildings are seldom taken into account at the time of purchase.

Although each plan will incur a financial cost, the electricity savings that can be realized may ultimately equal or exceed that of the initial cost after a number of years in operation. As a result, accurate calculations of each plan’s initial costs and their overall final financial benefits, using the simple Life-Cycle Cost method (LCC method), will likely ensure that they will be implemented in the energy saving renovations. For this paper, the initial outlay costs and the total electricity savings are taken into account in the LCC costs. If the electricity savings are greater than the initial costs, the plan is financially beneficial and should be recommended for application to an actual project. However, if the savings are less than the initial costs then the plan should not be considered.

The cost of electricity and materials is dependent on many factors (e.g. market, inflation, etc.), and the cost data in the paper is cited from 2007 market prices. Any added costs due to the interest rate on the loan for the initial investment can be counteracted or exceeded by the increased value of the property due to rapid economic development in China. As a result, the present simple LCC method used in the paper does not include the interest and inflation rate.

In 2007 the price of electricity was 0.53 ¥RMB/(kWh) (Hangzhou city price web, 2007), and the initial costs of the six plans are derived based upon the calculations of professional companies.

The final reduction of each plan’s costs will be calculated as follows: Multiplying the annual cost reduction for electricity saving by 40 years, and subtracting the initial cost produced in renovations. The results are shown in Table 8.

The final results of most plans are positive from an economic point of view with only the last plan being economically adverse. Green surfaces for envelopes will be advocated in future renovations. Plan 3 can be achieved through various methods or materials and exorbitant methods, such as the use of aluminum blinds should be excluded, while economical measures such as fabric or timber curtains should be encouraged.

3.4 Suitable plan

The most suitable plan should be a blend of the most promising measures dependant on the analysis of the six plans/measures as follows:

1. Insulation of the roof by adding insulation material (e.g. 40mm XPS) onto the roof. This measure appears to be the most effective measure with a high impact on heat and cold demands, in terms of economy, energy and the environment, since the roof surface represents a large part of the building envelope. The insulation layer should be safeguarded by reinforced concrete and light colored paint or ceramic tile applied to reduce the absorption coefficient of sunshine.

2. Insulation of exterior windows by substituting plastic double windows for old ones. Because the thermal performance of the existing windows is the least favorable part of the building’s envelope, and the windows account for a considerable part of the envelope, heat exchange occurs quite easily through the weakly resistant windows. Additionally, sunshine also affects the interior temperature of the building. The present window frames, made from aluminum, are excellent for transmitting heat, but disadvantageous in preserving it, and should in any case be replaced.

3. Insulation of the exterior walls by installing insulation material (e.g. 10mm XPS) on them. Exterior walls account for the greatest portion of the building’s envelope, so their thermal performance directly determines whether the interior environment is comfortable or not. Also the insulation layer should
be safeguarded by cement mortar and the surface of exterior walls covered by a light colored paint or ceramic tile to reduce the absorption coefficient of sunshine.

(4). Reducing the shape coefficient of the building by enclosing the stairs. Although the effect of these secondary measures is not as remarkable as the previous one, it should also be advocated because the analysis has proven that it will be beneficial in terms of energy saving, friendly to the environment and economical.

(5). Reducing the shadow coefficient SC in the summer by utilizing unfixable curtains or blinds. In order to acquire the optimum result, an analysis like that done above must be completed. The reason for this is that various curtains or blinds made from different materials will have various results. Some of which may be unfriendly to the environment, and/or uneconomical as well.

Despite the fact that painting may be an uneconomical measure, it has to be included into Plans 1 and 3 to ensure an attractive building appearance.

3.5 Simulation for the entire subject building

The following is a description of the subject building's thermal variables after being improved under suitable renovation plans.

(1) The shape coefficient is 0.32.
(2) The ratio of exterior windows/wall area and the K and SC of exterior windows are shown in Table 9.

| Orientation | South | North | West | East |
|-------------|-------|-------|------|------|
| Ratio       | 0.35  | 0.29  | 0.18 | 0.18 |
| K           | 2.85 [W/(m²·K)] |       |      |      |
| SC          | 0.70 in winter | 0.30 in summer |      |      |

(3). The K and D of the roof are 0.672 W/(m²·K) and 2.376 respectively.
(4). The mean K and D of the exterior wall are 1.310 W/(m²·K) and 3.176.
(5). The absorption coefficients of the roof and exterior walls' are 0.40, 0.40.

After completing the simulation with the above data, the total energy consumption for space heating and cooling of the suitable plan is 48.77 kWh/(m²·yr), thereby complying with the standards requirement of 56.40 kWh/(m²·yr). At the same time, the expectation of the entire subject building to reduce annual energy consumption, CO₂ emissions and costs over the next 40 years after renovations can be found in Table 10.

The overall effect of the suitable plan is very encouraging, with a 46.28% reduction of the annual energy consumption for space heating and cooling, an approximately 44% reduction of CO₂ emissions and a 26% increase in savings.

4. Conclusion

4.1 Conclusion of the research

The study has demonstrated that a significant reduction potential of energy savings and environmental and economic advantages can be made from high-performance building envelopes.

(1). Since the renovation of existing old residential buildings is unavoidable now and in the near future, it is prudent to take into account the renovation and energy savings as a whole in order to increase the attractiveness and positive consequences of energy saving renovations. As such, there is expected to be a shift in emphasis from improving the energy efficiency of new residential buildings towards the renovation and maintenance of existing ones.

(2). A great potential for energy savings exists in Chinese residential buildings due to the fact that most of these structures were constructed before 2000 when the first important demands regarding the energy performance of buildings were introduced. Since many buildings in China face comprehensive renovations in the coming years, relatively inexpensive and cost effective energy-saving measures such as those listed in this paper should be taken advantage of. The resulting benefits will positively affect both a reduction in energy consumption and financial savings.

(3). The greatest energy saving's potential can be achieved by upgrading the insulation performances of the existing buildings' envelopes. Upgrading the poorest thermal performances has the greatest potential to reduce energy consumption.

(4). The most promising plans should be combined so that the target standards can be realized. All packages should include the requirement of additional insulation for the roof, exterior walls and windows.

(5). The study also shows that extra environmental loads due to a greater use of insulating materials will be paid back within a few years with consistent social benefits, if the life cycle of the building is taken into account.

The possible economic, social and environmental potential through refurbishment of all existing residential buildings built before 2000 in Hangzhou city is substantial by any measure and should be seriously considered.

4.2 Future plan

The findings regarding the energy consumption of the subject building are only theoretical. Different lifestyles from those used in the simulation will exaggerate or alter the results. Further research utilizing more accurate and factual data of the building, should be carried out within this year.

This paper discusses only one building, therefore the results may not be applicable to other typical buildings. In the future, more typical buildings must be studied as subject buildings in order to provide additional valuable information.
Additionally, the results of this study are limited due to the lack of a comprehensive Chinese database on the conversion factors between various energy/materials and embodied energy/CO₂ emissions. We expect that a Chinese database will soon be available in order to promote energy savings in all the various trades and occupations of China.

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