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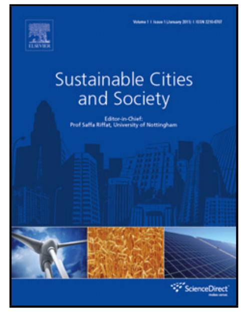

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Life cycle assessment of white roof and sedum-tray garden roof for office buildings in China

Dachuan Shi[a], Yafeng Gao[a*], Rui Guo[b], Ronnen Levinson[c], Zhi Sun[d], Baizhan Li[a]

[a] Joint International Research Laboratory of Green Building and Built Environment, Ministry of Education, Chongqing University, 400044, Chongqing, PR China

[b] Department of Civil Engineering, Aalborg University, 9220, Aalborg, Denmark

[c] Heat Island Group, Lawrence Berkeley National Laboratory, 1 Cyclotron Road, MS90R2000, Berkeley, CA 94720, USA

[d] Research Institute of Standards and Norms, Ministry of Housing and Urban-Rural Development (MOHURD), 100835, Beijing, PR China

* Corresponding author

Email Adress: gaoyafeng79@126.com

Tel: +86 02365128079

Highlights:

- A life-cycle cost analysis was conducted for white and sedum-tray garden roofs
- The application prospect of two roofs in four Chinese climate zones were analyzed
- White roofs were more cost-effective than grey roofs in warm winter climate zone
- Sedum-tray garden roofs were found to be globally more expensive than grey roofs
- Policies accounting for these findings are proposed for planners and managers

ABSTRACT

White roof (WR) and *Sedum lineare* tray garden roof (STGR) have been convinced to improve the energy-efficiency and provide various benefits for conventional impervious grey roofs. Some national and local standards have standardized and recommended these technologies in existing building retrofits, however, they do not include assessment and choice of a particular roof retrofit in different climates. This paper presents a 40-year life-cycle cost analysis (LCCA) of an office building roof retrofitted by adding either WR or STGR over an existing grey roof in five cities, located in four Chinese climate zones. The LCCA find that the WR retrofits exhibit positive life-cycle net savings (NS) in warm winter zones, ranging 5.7–35.1 CNY/m^2, and STGR retrofits have negative NS of -81.3– -16.7 CNY/m^2 in all climate zones. The NS of both WR and STGR generally tend to improve as one moves from the coldest cities to the warmest cities.

LCCA results suggest that adding new building codes concerning crediting or prescribing WR and STGR retrofits into office buildings with grey roofs in hot summer climate zones and warm winter zone in China, respectively. And featured by more specific requirements, the localized Technical Norms help promote the implementation of new building codes.

Key Words

Roof retrofit; White roof; Sedum-tray garden roof; Life-cycle cost analysis; Building codes.

1. Introduction

As of 2010 and 2013, China has become the world's largest energy consumer (21% of the global total) and carbon emitter (28% of the global total), respectively [1]. By 2014, 33% of the total energy use and 40% of all CO_2 emissions attributed to the drastic growth of office space to 10.7 billion m^2 in China [2][3]. The energy consumption of office buildings (excluding heating) leads all building types [4]; this contributes to global warming and the summer urban heat island (UHI) effect, and results in heat-related deaths, peak-hour power demand increases, and other ecologically adverse impacts [5]. In response to the current energy usage situation, the Chinese government is comprehensively promoting the energy savings and green retrofitting of existing office buildings during the "13th Five-Year Plan" period [6].

The solar reflectance change of urban surface attribute to the rapid urbanization on building sectors and environments creates a significant difference in the air temperatures of cities versus their countryside. Conventional impervious grey roofs in China (with an albedo of about 0.10 to 0.20) absorb roughly 80% of solar infrared radiation portion of which is dissipated to heats the roofs and atmosphere, increasing the cooling costs of air conditioning systems, and heightening the effects of global warming and UHI [7]. High albedo (solar reflectance) white roof (WR) or sedum-lineare garden roof (STGR) are commonly considered to mitigate the detrimental effects associated with grey roofs [5][8].

The selection of WR (albedo of 0.55–0.90) can reduce the heat gain of a structure, consequently reducing the cooling load in a conditioned space [9], Levinson et al. [10] reported annualized cooling site energy savings measured about 0.6–6.4 kWh/m^2 from several WR retrofits in the United States (U.S.). However, boosting the albedo of roof surfaces can also result in higher heating costs, referred to as the winter heating penalty, especially in cold climates [11]. Simulations of WRs on commercial buildings across the U.S. determined that the energy cost savings varied with climate zones. Savings in Hawaii (Aw-tropical wet/dry season climate, \$1.14/$m^2\cdot$y) were generally greater than those in Minnesota (Dfb-humid continental climate,

\$0.13/m^2·y)—except in Alaska (\$0.32/m^2·y), where annual energy cost savings were enhanced by the low price of heating gas and high price of electricity for cooling [10].

Raising roof albedo also mitigates the summer UHI and provides "global cooling" by reducing solar heating of the atmosphere, which can reduce the carbon emission and provide environmental reliance and sustainability [12]. Akbari et al. [13] conducted simulations increasing the albedo of urban locations on the basis of two independent estimates of the spatial extent of urban areas and found the resulting global cooling effect ranged 0.01–0.07 K, corresponding to an equivalent one-time reduction in CO_2 emissions of 25–150 billion tons.

Garden roof can provide evaporative cooling as well as effective thermal insulation, thereby providing year-round energy savings [8]. Garden roofs offer little, if any, global cooling potential because the albedo typically ranges 0.16–0.26 [14], and the cool moist air above the garden surface eventually condenses as rain, releasing heat [15]. Garden roofs also offer other environmental benefits relative to WR, including UHI mitigation, stormwater control, air quality improvement, and biodiversity; they also provide recreational, agricultural, and landscape value to the community [16]. Stormwater management is widely considered as an important benefit of garden roofs. Tang [17] estimated that a 100 mm soil layer in a garden roof can hold water of approximately 16–22 mm. Adams et al. [18] investigated saving 35% of the original stormwater fee (\$0.90/m^2·y) in Portland, Oregon by installing a garden roof.

Previous studies on the conventional garden roof have found that garden roofs justified sustainable construction product due to their environmental benefits, but compete for their cost disadvantage in building budgets [19]. Peng et al. [20] estimated that extensive garden roofs have a positive net savings of \$10.8/m^2·y in Hong Kong, while Sproul et al. [5] estimated that extensive garden roofs have a negative 50-year net savings of \$71.0/m^2 in the U.S. because of the high initial costs and insurance premiums. The high costs of extensive roofs also make the government and individuals hesitant to promote garden roofs [5]. Compared with a common garden roof, sedum-tray garden roof (STGR) mainly consists of sedum-tray trays which can be placed on top of the waterproofing protection layer and connected to drains (Figure 1). Therefore, the light-weight and modularized STGR which offers low installation cost and easy maintenance thrives in a variety of climates have been launched into the market [8][21] The advantages of the STGR system have been recognized in engineering practice [8]. In this study, STGR is studied from an economic perspective.

Figure 1. Structure diagram of (a) an STGR, and (b) a common extensive green roof.

In general, to reduce the environmental damage created by grey roofs, WR and STGR are implemented widely to achieve energy savings with strategic environmental, economic, and social benefits [22]. However, although the lifecycle assessment is applied to quantify and improve this sustainability in construction, a lifecycle benefit-cost value representing a unit of area comparisons among these three roofing systems are still limited, most previous life-cycle cost analyses have focused on a single climate zone, or a single roofing system. There have been some studies conducted to compare the economic benefits between grey roofs and white roofs [10][23][24][25][26] or green roofs [16][27], and these studies almost focus on specific energy efficiency [28], environmental benefits [29][30], life-cycle analysis [5][31], and social cost-benefits [16], respectively. Therefore, with the absence of systematic comparative study on the life cycle assessment of STGR and WR retrofits in all Chinese climate zones, it is difficult to provide a reference for the choice and promotion of existing office building roof retrofits in different climates, the guidelines and standard protocol for the selection of roof retrofit systems to suit a particular climate zone have not been clearly established to date.

In this paper, DesignBuilder v5.3, a front end to the EnergyPlus building energy model (EnergyPlus 8.6), is used to simulate the annual conditioning (both heating and cooling) energy savings of a building model based on a representative office building. Using the results of this simulation, a 40-year life-cycle cost analysis (LCCA) is conducted to provide an economic comparison of the cost-effectiveness of retrofitting a roof with WR and STGR systems for cities in four distinct climate zones in China, and provides policy recommendations based on this analysis. This study can bridge the gap in understanding observed in the current literature by quantifying the abstract, scatter environmental benefits of these technologies into proper lively, imaging, and comprehensive economic values, thus providing a set of scientific criteria to aid building managers and planners in selecting environmentally friendly roofing systems for new and existing buildings.

2. Materials and methodology

The annual energy consumption of a representative office building was first simulated with three different roofs (grey, WR, and STGR systems) in five Chinese cities spanning four climate zones: severe cold (SC), cold (C), hot summer/cold winter (HSCW), and hot summer/warm winter (HSWW) zones, respectively (Figure 3). The climate zone classification used in this study is based on Design Standard for Energy Efficiency of Public Buildings in China (GB50189-2015), which is widely used in many studies of indoor thermal environment and building energy consumption in China. As Cui et al. [32] proposed buildings in the temperate zone had little cooling and heating demand, the temperate zone is excluded in this study. Energy savings were calculated by subtracting energy uses with WR and STGR systems from those with a grey roof; energy cost savings and emission reductions were estimated from energy savings. The simulation results were then used to determine the 40-year lifecycle net savings (NS)[1] for an office building roof retrofitted with a WR or STGR in the different climate zones.

Figure 2. Chinese climates zones and cities [33].

We considered two cities (Xiamen and Shenzhen) in HSWW because Gao et al. [34] have ensured that WR can save energy in both HSCW and HSWW in China as the heating loads in those climate regions are quite low. Moreover, the Xiamen and Shenzhen Municipal Government both call for vigorous promotion of green roof, especially the tray garden roof.

[1] Life-cycle net savings (NS) are calculated as the present value of annual savings streams minus that of the installation cost premium(s). A positive NS indicates the WR or STGR is more cost-effective than a grey roof, while a negative value indicates it is less cost-effective.

2.1. Simulations

A representative office building model was constructed in DesignBuilder v5.3; building model and parameters are detailed in Figure 2 and Table 1. The building model was based on prototypes of a concrete-slab (foundation, walls, and roof) office building in China developed by Gao [34]. The envelope characteristics, ventilation and infiltration rates, internal loads, operating schedules, and cooling and heating setpoints comply with prescriptive requirements or recommended design values in current Chinese building energy efficiency standards [35], and were made to reflect the typical details in each different zone, as shown in Table 2-3.

Figure 3. (a) Axonometric projection and (b) plan of the top floor of the representative office building simulated.

Table 1. Characteristics of the representative office building simulated.

Table 2. Maximum and set values for the thermal transmittance (W/m^{2}K) of building envelope components permitted in various Chinese cities [33][36][37]38][39][40].

Table 3. Roof and wall construction (listed outside to inside) of a representative office building in each city [38].

Table 4. Specifications of Sedum lineare planting modules [8].

The HVAC system was designed based on Chinese building energy efficiency standards and is also detailed in Table 1 and Table 2. The occupancy hours were set as 08:00–18:00 local standard time from Monday to Friday, excluding holidays. The setpoint temperature was 26 °C in summer and 20 °C in winter. Space cooling was provided by a split direct expansion air-source heat pump with a cooling coefficient of performance (COP) of 3.2, which is typical in China [34]. The heating system was determined by the climate zone: a coal-fired boiler with an efficiency of 80% was used in severe cold and cold zones, while the same air-source heat pump (heating COP of 2.8) used for air cooling was used for heating in the other two climate zones.

The building model was simulated with three different roofs. The grey roof (with an aged albedo of 0.20) was used as the reference roof. The WR system used consisted of a white elastomeric coating (aged albedo of 0.60) installed on top of a grey roof, while the STGR system was made of *Sedum lineare* planting modules with the values described in Table 4.

Space heating load and space cooling load savings were computed as the load of the building with the reference (grey) roof minus that of the building retrofitted with the WR or STGR. Load savings were then used to estimate site energy savings, source energy savings, energy cost savings, and emissions reductions.

2.2. Life-cycle cost analysis

A 40-year LCCA was conducted to determine the NS for an office building roof retrofitted with a WR or STGR system in the target cities spread through four Chinese climate zones. Some previous works indicate that the use of a garden-roof is expected to last for more than 40 years compared to 20 years for a white membrane roof or a grey roof, made up with a concrete and waterproof layer [5]. Various studies in the U.S. have found that the WR has a service life of 15–20 years [41], and managers typically prefer to just to replace the roof surfacing material at the end of its service life, rather than continuously maintain the roof [8]. Our 40-year LCCA includes at least once replacement cost for the WR, and this study assumes that roof is made white according to *Technical specification for application of architectural reflective thermal insulation coating JGJ/T359-2015*, after applying 2–3 layers of architectural thermal insulation reflective coating (each layer ≥ 2 mm) over an existing grey roof, then a white waterproof layer is specified.

The analysis includes the installation, replacement, and maintenance costs of the roofs; energy cost savings (simulated for both cooling and heating); reduction in emissions of CO_2, NO_x, and SO_2 from power plants and increase in emissions from coal furnace in cold zone; equivalent CO_2 emissions reduction from carbon sequestration and global cooling; and the stormwater control benefits. Following Sproul et al. [5], we note that other benefits of these roofing systems, including biodiversity, aesthetic value, and increased property value can be difficult to quantify, and are thus not taken into account in this study.

To calculate the net present value (NPV) of roof comparison for a 40-year LCCA of WR and STGR system retrofits, we assume: (a) constant annual energy cost savings based on latest energy prices; (b) constant annual retrofit maintenance cost; (c) a 20-year service life for the WR; and (d) a 40-year service life for the STGR. Therefore, the NPV of the life cycle cost savings is given by:

$$NPV = \sum_{i=1}^{40} \frac{(C_i \text{-} C_0)}{\left(1+r\right)^i} \tag{1}$$

where C_i is the annual profit of the WR or STGR compared to grey roof including energy cost savings, carbon emissions reduction savings, and stormwater-related savings, in CNY/m^2·y; C_0 is the annual cost including installation, maintenance costs (STGR), and replacement costs (WR), in CNY/m^2·y; the real (inflation-adjusted) annual rate of return r is set to 3% [42]; and the number of years in the life cycle is set to 40.

2.2.1. Installation, replacement, and maintenance costs

Installation costs occur in both existing roof repair and replacement with a white roof or STGR at the end of its service life, and usually consists of the coating cost and labor cost. Sproul et al. [5] proposed that coating disposal costs should occur in this case as well, but no disposal costs are present because grey roofs in China are typically simply covered with a new membrane. Similarly, no disposal costs occur when installing a garden roof because the trays can be directly placed on the roof surface.

White roofs are widely known as an affordable and simple alternative to grey roofs. The costs of the coating itself can be quite different depending on the specifications, type, and manufacturer selected for use. Over its service life, the most expensive thermoplastic elastomeric membrane (\$20/m^2) could be \$7.4/m^2 cheaper than installing the cheapest built-up bituminous roofing in some cases [5], while the median market price (materials) of white coating in China is approximately 36.3 CNY/m^2 (\$5.48 /m^2) [43]. Compared to common extensive garden roofs with installation costs of \$108–248/m^2 [44], STGR enjoys a considerable cost advantage at about \$10.4/m^2 installation cost[2], which yields only 10% of extensive garden roofs above [43].

A routine maintenance cost of 1.34 CNY/m^2·y (\$0.20 /m^2·y) required including repair leaks and cleaning gutters/downspouts [5]. Corresponding maintenance costs occur in the grey roof, WR, and STGR systems, that is, there is no additional maintenance cost of WR compared to the grey roof. However, additional maintenance needs of STGRs, including simple irrigation, costs 2.00 CNY/m^2 [28], or about 10 % of the median of the 40-year maintenance cost of an extensive green roof (\$2.90 /m^2·y) [5]. While a common extensive green roof has its drainage layer under the soil, the drainage layer of an STGR is located in the bottom of the container and can be easily installed, cleaned, and repaired (see Figure 1). To accomplish these maintenance tasks, laborers are required to perform a minimum of three visits per year.

2.2.2. Heating and cooling site energy and source energy cost savings

Here we repeat the methodology applied in our earlier study [34]. Heating and cooling site energy savings were evaluated by dividing the heating and cooling load savings by building- and location-appropriate heating and cooling COPs. In severe cold and cold zones (Shenyang and Beijing, respectively), the office buildings were assigned coal heating (heating COP of 0.8 [44]) and split-system electric cooling. In the hot-summer locations (Chongqing, Xiamen, and Shenzhen), the office was assumed to use split-system electric heating and cooling.

Heating and cooling source energy savings were calculated by multiplying each value for site energy savings by the appropriate source-to-site ratio (f = 3.147 for electricity and 1.05 for coal), then summed to yield source heating/cooling conditioning energy savings. Likewise, heating and cooling energy costs savings (CNY per unit conditioned roof area) were computed by multiplying each site energy savings by the appropriate energy price (Table 5), and then summed to yield conditioning energy cost savings.

[2] At the July 2018 exchange rate of 6.62 CNY to 1 USD.

Table 5. Electricity prices (CNY/kWh) and coal heating prices (CNY/kWh) in each simulated city.

2.2.3. Power plant emissions savings and CO_2 emissions trading price

The CO_2, NO_x, and SO_2 emissions reductions from heating or cooling energy savings were calculated by dividing the heating and cooling source energy savings by the appropriate energy transmission efficiency and pollutant emissions factors (Table 6, 7), as shown in Eq. (2), and then summed to yield the emissions savings for each pollutant (i = CO_2, NO_x, and SO_2). That is,

$$M_i = \frac{E \times k_i}{\eta} \tag{2}$$

where M is the annual emissions reduction, in kg; E is the annual heating or cooling site energy savings, in kWh; k is electricity emissions factor, in kg/kWh; and η is the energy transmission efficiency (0.9 for electricity and 1.0 for coal).

Table 6. Electricity emissions factors (mass of pollutant emitted per unit non-base electrical energy supplied to the grid) from [34].

Table 7. Coal emissions factors (mass of pollutant emitted per unit of fuel energy consumed) from [34].

As of February 2017, carbon trading markets exist in seven provinces and cities in China: Guangdong province, Hubei province, Shenzhen city, Beijing city, Shanghai city, Tianjin city, and Chongqing city. Although Shenzhen is part of Guangdong, it has its own carbon trading market. The carbon trading market was extended throughout China by 2016 [56]. Table 8 shows the lowest carbon trading price in each considered location. We observe that the carbon price in China is about one-thirtieth that in Europe [57]. Notably, though the current work calculates the value of carbon savings, the LCCA omits the values associated with NO_x and SO_2 savings as these emissions are yet not traded in China.

Table 8. CO_2 trading prices. The prices in Shenyang and Xiamen were assumed to equal that in Chongqing, which had the lowest price in China as of February 2016.

The annual equivalent CO_2 emissions reduction from carbon sequestration is given by the median of the reported data as 1.23–2.48 kg/m^2 [59]. Moreover, Sproul et al. [5] compared white roofs (aged albedo of 0.60) and garden roofs (aged albedo of 0.20) to black roofs (aged albedo 0.05–0.10) and found the global cooling benefits of WR cause by CO_2 emission reduction only apply to the first 40-year life-cycle, yielding emissions reduction benefits of 2.00 kg/m^2 and 0.68 kg/m^2, respectively.

2.2.4. Stormwater-related benefit

As an integral part of the urban ecosystem, an STGR can be an effective savings of a building stormwater management plan, because the canopy and substrate can capture and store the outflow of water. This paper estimates the water conservation in the canopy and substrate by the method of water balance [60], then applies sewage treatment charges based on 227 samples in China (median of 0.8 CNY/t) [61] to determine stormwater-control cost savings. It is assumed the use of an STGR reduces the annual stormwater fees (Table 9) [62] comes from the annual transpiration water (about 0.39 t/m^2) [63] and water conservation (at least 61.5% of runoff) effects [64].

Table 9. Annual stormwater-related cost savings of STGRs in five cities in China.

3. Results

3.1. Annual air conditioning load, site energy, and source energy savings

Raising the roof albedo to 0.60 (aged WR) from 0.20 (aged grey roof) decreases the annual cooling load by 1.14–3.75 kWh/m^2, annual cooling site energy use by 3.61–14.00 kWh/m^2, and annual cooling source energy use by 3.75–14.54 kWh/m^2 (where Shenyang < Chongqing < Beijing < Xiamen < Shenzhen), respectively. It also increases the heating load by 0.01–4.46 kWh/m^2, annual heating site energy by 0.03–4.68 kWh/m^2, and annual heating source energy by 0.03–3.57 kWh/m^2 (where Shenzhen < Xiamen < Chongqing < Shenyang < Beijing), respectively.

Adding the sedum trays to the grey roof decreases the annual cooling load by 2.28–7.89 kWh/m^2, annual cooling site energy use by 0.69–2.40 kWh/m^2, and annual cooling source energy use by 2.20–7.60 kWh/m^2 (where Shenyang < Chongqing < Beijing < Xiamen < Shenzhen), respectively. It also decreases the heating load by 0.03–4.49 kWh/m^2, annual heating site energy by 0.01–1.70 kWh/m^2, and annual heating source energy by 0.02–5.90 kWh/m^2 (where Shenzhen < Xiamen < Chongqing < Beijing < Shenyang), respectively (see Figure 4).

Figure 4. Annual cooling and heating load, site, and source energy savings after applying a WR or STGR retrofit to the representative office building.

Some results from previous studies referred to ensure the validity of our results. Gao et al. [34] conducted the energy consumption measurement case studies including the WR and grey roof in office buildings in Chongqing (HSCW) in 2012, the air conditioner in test room with WR saved about 0.05 kWh/m^2·d less electricity than that in room with grey roof in cooling season, and energy savings of WR reported the cooling energy savings in Beijing and Chongqing decreased by WR ranged 1.65–1.59 kWh/m^2, as opposed to -5.85–-0.30 kWh/m^2 of heating energy savings, respectively. These measurement and calculation results are similar to the simulation results in this paper. And in 2015, a WR, grey roof and STGR were applied to the three unoccupied air-conditioned top floor rooms of an office building in Guangzhou (near Shenzhen, HSWW). The annual cooling energy savings of WR and STGR can be calculated about 4.86 kWh/m^2 and 3.60 kWh/m^2, respectively [66]. Although we found the measurement results were are 0.44 kWh/m^2 and 1.20 kWh/m^2 greater than corresponding calculated results of WR and STGR, we believe the calculation results are reasonable agreement for an aged WR and STGR, because the WR and STGR applied to the tested rooms were just finished on May 2015, and the tested rooms were unoccupied without any plug loads, while the calculated models were on-use with occupancy, lighting, and other equipment.

3.2. Economic comparison of WR and STGR retrofits

We can now apply Eq. (1) to each of the five case simulations, with the results shown in Figure 8, to compare the lifecycle cost savings attained by using a WR or STGR above a grey roof. We can also compare and analyze the NS in present values for WR and STGR in the five cities from different climate zones in Figure 5.

Figure 5. The 40-year lifecycle NS of a WR or STGR retrofit of the representative office building.

Figure 5 shows the life cycle NS when using WR and STGR in each case. Excluding the economic value of SO_2 and NO_x emissions savings, the following findings can be stated:

(1) The cost-effectiveness[3] of both WR and STGR tend to improve as one moves from the coldest cities to the warmest cities (left to right in Figure 5), excepting Beijing.

(2) The 40-year lifecycle NS for the WR retrofits ranged from -35.9 CNY/m^2 (Shenyang, SC) to 35.1 CNY/m^2 (Shenzhen, HSWW), and the results across the five cases are greater than the differences. The WR exhibits poor cost-effectiveness in SC, C, and HSCW; however, the cost-effectiveness of a WR system in HSWW is much more advantageous. The winter heating penalty of a WR increases the energy costs in cold winter areas and results in poor cost-effectiveness. In HSWW, however, the heating load and demand are low, and as a result so are the negative effects of WR usage.

(3) The 40-year NS of STGR retrofits ranged from -81.3 CNY/m^2 (Shenyang, SC) to -16.7 CNY/m^2 (Shenzhen, HSWW) (see Figure 5), indicating that the use of an STGR offers poor cost-effectiveness in China, lower than that of a WR in every climate zone evaluated.

The results agree with those from other researchers. For example, Zhang et al. [44] confirmed that cool roofs are cost-effective in Singapore, while Sproul et al. [5] found a positive

[3] Positive NS during 40-year lifecycle.

50-year NS of white roof (\$25 /m^2), and a negative NS of green roof (-\$71 /m^2) in a study of 22 cases in the U.S.

Figure 6. Annual CO_2, NO_x, and SO_2 emission savings per unit conditioned roof area after applying a white roof or garden roof retrofit to the office building prototype.

It is important to note that some default values were used in these calculations for values such as the CO_2 emissions reduction from carbon sequestration and global cooling benefits. Also, the cost savings of SO_2 and NO_x emissions reductions, which cannot be evaluated without nitrogen and sulfur trading mechanisms, were ignored. Thus, the results of this analysis will change as more real-world data can be included.

Figure 7. Comparison of WR and STGR retrofits during 40-year NS in present values for the representative office building in five cities from different Chinese climate zones.

Figure 7 represents the accumulated default values depicted in Table 10 for all five subject cities, illustrating the different costs and benefits in the different climate zones. Values below the zero value on the vertical scale indicate increased costs (negative net saving), while the positive values indicate net savings over the 40-year life cycle. Thus, if the quantity above the zero value is greater than that below, the benefits outweigh the costs, the NS is positive, and the roof retrofit can be considered cost-effective. Accordingly, a higher NS indicates a more cost-effective roof retrofit in the given city.

Table 10. Default value inputs for life-cycle cost analysis.

3.2.1. Roof installation and maintenance costs

As shown in Figure 7, because a WR has to be replaced once during the 40-year life cycle analysis period, a WR has higher installation cost premiums than an STGR. The installation cost difference is relatively modest, ranging from 9.9–13.6 CNY/m^2 (Table 10, lines 1 and 2). Moreover, a present value of the maintenance cost over the 40 year life-cycle for an STGR is 46.2 CNY/m^2.

3.2.2. Energy cost savings

Generally, the 40-year lifecycle NS of WR and STGR are illustrated to increase monotonically when one moves from the coldest city to the warmest city (left to right in Figure 5), as well as the roof thermal transmittance U increase (Table 1). However, the deviation of Beijing results from the general trend is depicted largely due to the influence of energy cost savings which was the lowest of 1.40 CNY/m^2 (Figure 7), as the U of Chongqing (0.63 W/m^2•K) is higher than that in Beijing (0.55 W/m^2•K), and the lowest average monthly temperatures for C (−5°C) are 10°C lower than those in HSCW, the heating site penalties of WR in C are 5.80 kWh/m^2 bigger than those in HSCW (Figure 4), which lead to more annual energy consumption of 3.67 kWh/m^2 in C, as opposed to annual energy savings of 1.58 kWh/m^2 in HSCW (Figure 4). Moreover, another factor such as the price of energy may also be playing a part, as the low price of coal heating and the high price of electricity for cooling in C results in higher energy cost savings in SC than in C (Table 5). These results are similar to those of simulations of energy cost savings in different climates conducted by LBNL in the U.S. [67].

With regard to STGR, due to the additional evapotranspiration cooling provided in summer and the heating penalty eliminated by thermal insulation of sedum-tray module in winter (Table 10), the annual energy savings exceed others at 7.32 kWh/m^2, thus the energy cost savings was highest at 69.6 CNY/m^2 in Beijing (C). Additionally, the cooling load is dominant and heating load is low in HSWW; thus a WR saves 0.85-2.19 CNY/m^2•y more in energy costs than an STGR as a result of its higher albedo.

3.2.3. CO_2 emissions trading savings

Carbon emissions reduction comprises power plant emissions reductions, the global cooling benefit included only in the first 40-year life cycle, and the equivalent CO_2 sequestered by the garden roof during its service life (see Figure 6).

Power plant emissions reductions are associated with the source energy and are detailed in Table 10. The WR retrofit contributes to more source energy consumption in SC and C (Figure

6), the energy cost savings are still positive in both locations, and even greater in SC than in C because office buildings in Beijing were assigned coal heating. The ratio of source energy savings to heating load savings (f/C_h)[4] of coal heating is 1.5, higher than that of an electric heat pump (0.9), magnifying the heating source energy penalties paid when using a WR and the heating source energy savings realized when using an STGR.

The CO_2 emissions savings from the WR retrofit were negative for cities in SC, which was the result of negative coal heating savings. As discussed in Section 2.2.4, WRs have greater global cooling benefits than garden roofs because the albedo of a WR is up to three times that of a garden roof. However, an STGR also provides carbon sequestration, which yields a modest life-cycle cost savings of 0.02–0.1 CNY/m^2. As noted by Gao et al. [34], coal CO_2 emissions factors are independent of the combustion system type and boiler firing configuration [68], but the coal NO_x and SO_2 emissions factors used here are for spreader stokers characterized by the U.S. EPA [69] and may or may not represent actual building furnaces in China. Taking into consideration all the parameters discussed above, the life-cycle value of CO_2 emissions trading savings from an STGR is about 0.69–2.84 CNY/m^2 less than that of a WR.

3.2.4. Stormwater-related benefits

Savings from avoiding stormwater-related costs are a major benefit of an STGR, the savings value is decided by garden-roof types and local precipitation. The growth medium of the STGR retains water which is later evaporated (approximately 0.39 t/m^2·y). The extra stormwater retention capability of the STGR results in an NS of 9.6–15.2 CNY/m^2, which is much higher in southern cities due to their abundant precipitation. The stormwater-fee cost savings resulting from the use of an STGR, therefore, offers an additional advantage. Additionally, Sproul et al. [5] found that a green roof can also reduce the size of stormwater drainage system needed, the equipment

[4] f represents the site-to-source energy ratio and C_h represents the heating COP.

downsizing results in a cost savings of \$36.0 /m^2, the benefits occurred just in new buildings or major reconstruction, and excluded in this case of roof retrofit.

4. Discussion

4.1. Choice of roof retrofit

The current work compares WR and STGR systems with respect to their cost-effectiveness and energy savings. The LCCA conducted here quantifies and monetizes the costs and benefits to the extent possible to provide a clear economic comparison, indicating that both WR and STGR systems offer energy savings and environmental benefits over conventional grey roofs. However, these systems are not generally cost-effective, except for the WR system in the HSWW. Therefore, policy makers in such climate zone can be informed straightforwardly that the application of WR can be directly helpful in aiding their cities in addressing global and local climate-change challenges.

Additionally, the WR retrofits offer poor cost-effectiveness in SC and C result from winter heating penalty, and in HSCW. Gao et al. [34] suggested that WR should be prescribed in building energy efficiency standards for HSCW in China because of WR on office building yields source energy savings of 4.1–10.2 kWh/m^2·y in HSCW and HSWW. Although the energy simulation finds the similar energy savings of 5.0 kWh/m^2·y in this study, the LCCA results indicate the annualized cost premiums for WR is 0.88 CNY/m^2·y in such climate zone where its energy cost savings cannot surpass its cost. In case continued use of grey roofs in HSCW and HSWW will result in increased incidence of heat waves, risking citizen lives, decision makers there should be focused on promoting the use of WRs to realize their increased energy cost savings (shown in Table 10) and global cooling effect, accepting the small annualized premium as a worthwhile cost. It is recommended that new construction or waterproofing replacement, consider the use of WR, which provides many positive benefits at no additional cost to new construction [44].

The LCCA results also indicate STGR system is less cost-effective than the WR system. Compare to STGR, WR offers an NS of 26.8–51.8 CNY/m^2 (see Figure 5). The annualized cost premium is just 0.67–1.29 CNY/m^2, and much less than those of conventional green roof in the U.S. (\$2.0–4.0/m^2) because of the relatively small initial costs [5]. There are deviations regarding the results, the STGR retrofit in Shenzhen (HSWW) (Figure 5) had a negative NS of 16.7 CNY/m^2, while Peng et al. [20] simulated large-scale green-roof installation in Hong Kong (close to Shenzhen), and found a substantially positive NS of \$10.8 /m^2. Possible reasons for this observation are: (1) lower carbon price (67.2 CNY/t in Hong Kong compared with 29.33 CNY/t in Shenzhen) results in lower carbon emission reduction in Shenzhen; (2) lower energy savings (7.62 kWh/m^2·y in Shenzhen compared with 48.0 kWh/m^2·y in Hong Kong) yielded lower energy cost savings; (3) district-scale extensive roof simulation presents much more savings of 3.31 USD/m^2·y from UHI mitigation [20], compared with median value of \$0.80 /m^2·y in other literature [16][23][26][27][29]. Therefore large-scale garden-roof installation can increase the cost-effectiveness of one garden-roof therein. Besides, the negative NS of STGR underestimates its true social advantages, including some health and aesthetic benefits that cannot be easily monetized.

Although in this study the observed NS and cost-effectiveness were not as advantageous as expected, it has become common for building managers to avoid grey roofs. When choosing a roofing option, decision makers should also take into consideration both the purpose and identity, because WR and STGR are most successfully applied in projects with completely different objectives. For example, a hotel designer can either opt for STGR that guests could enjoy when walking along the roof, or they can choose WR for both cost-effectiveness and simplicity. In other words, the choice of roofing systems depends more on the specific needs of the project than it depends on dry facts and statistics.

4.2. Policy implications

Since 2014, local energy efficiency standards in several southern provinces, such as in Hainan, Guangzhou, and Shanghai, have proposed credits for use of cool roofs and walls, or use of roof and wall vegetation, in public buildings [70]. Some national and local standards have standardized and recommended the WR and STGR, but not require, assess and choice of a particular roof retrofit in different climate zones. The Research Institute of Standards and Norms of MOHURD is now compiling *General Specification for Building Energy Efficiency & Renewable Energy Consumption* and *General Specification for Existing Building Envelope Retrofit* [71]. This presents opportunities to offer the following proposals:

(1) Add above-mentioned new building codes concerning roof retrofit into the part of *Building Energy Efficiency* and *Existing Building Envelope Retrofit*, which can compel social units and individuals to undertake ecological restoration obligations with respect to existing office building retrofits. Acceptance standards should be also added to shape and promote the formation of mature industrial chains and large-scale production, as well as the development of technical qualification methods for practitioners.

(2) Standardized and specific retrofitting requirements are highly suggested in the Technical Norms. Based on the current reform of the standard system, Technical Norms can be Mandatory Standards set by the country or the technical standards accepted by the industry. Featured by more specific requirements, the localized Technical Norms help promote the implementation of building codes.

(3) In order to ensure the sustainability of roof applications, it is imperative to improve other supporting measures of the rating system, assessment, and aging technical standards.

Moreover, the local government should formulate a comprehensive plan laying out office building roof retrofits to avoid blind spontaneous activity, and provide funding, intellectual, and policy compensation measures in order to incentivize office building roof retrofits, especially in terms of intensifying efforts to promote the application of new technologies (of which STGR is a prime example).

5. Conclusions

This paper conducted a life-cycle cost analysis on an office building roof retrofit by simulating the addition of a WR or STGR to the existing grey roof of a representative office building, concluding that the choice between a WR and STGR retrofit depends on the climate zone, local initial investment, operating and maintenance costs, as well as various environmental benefits. This analysis provides valuable reference and policy implications for policy makers by performing the first empirical comparison between the performances of these roofing systems in the different climate zones of China.

An economic comparison over a 40-year lifecycle indicates that substituting both an aged WR (albedo 0.60) and an STGR tends to improve as one moves from the coldest cities to the warmest cities, except for Beijing. The WR exhibits cost premium ranged from-57.2 CNY/m^2 to -27.4 CNY/m^2 in the central and northern areas of China (C > SC > HSCW), whereas the WR retrofits are certainly economical in HSWW (5.7 CNY/m^2 in Xiamen and 35.1 CNY/m^2 in Shenzhen). Meanwhile, a negative NS of STGR retrofits ranged from -81.3 CNY/m^2 (Shenyang) to -16.7 CNY/m^2 (Shenzhen), indicating that the use of STGR is not cost-effective. However, the annualized cost premiums are just 0.4-1.1 CNY/m^2 in HSWW, this annual difference is relatively small.

Although a WR retrofit appears to be more cost-effective than an STGR retrofit in all Chinese climate zones, decision-makers can also choose locally-selected roofs on the basis of case-by-case factors. That is, WR retrofits can be used as the preferred for its cost-effectiveness and global cooling in such climates, and STGR can be incentivized for its urban microclimate improvement, UHI mitigation, the air quality, soundscape design, stormwater management, and other community benefits.

The latest national and local energy efficiency standards, such as in Guangdong, Shanghai, Beijing, Jiangsu and Chongqing, standardize and credit WR and STGR retrofits for office buildings with grey roofs, however, they do not include assessment and choice of a particular roof retrofit in different climates. LCCA results suggest adding new building codes concerning crediting or prescribing WR and STGR retrofits into office buildings with grey roofs in hot summer climates (HSCW and HSWW) and HSWW in China, respectively. While current national energy efficiency standard and some local standards in HSWW, such as Hainan, neither credit nor recommend STGR for office buildings. Furthermore, the current aging rating system in Chinese standards, especially in terms of artificial weathering index, lags far behind the Energy Star (ES) and Cool Roof Rating Council (CRRC) in the US.

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Figure captions

Figure 1 Structure diagram of (a) an STGR; and (b) a common extensive green roof.

Figure 2 Chinese climates zones and cities.

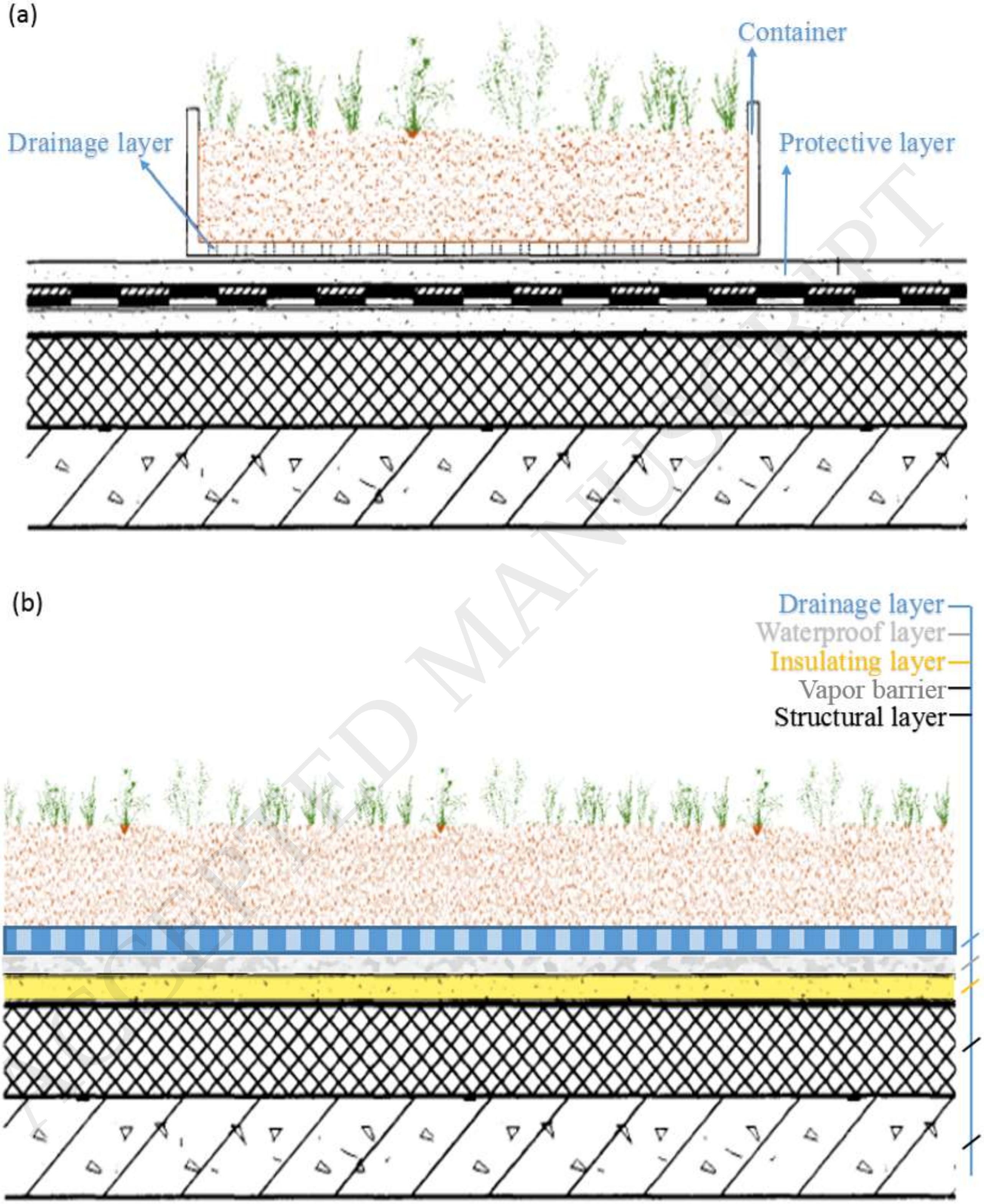
Figure 3 (a) Axonometric projection and (b) plan of the top floor of the representative office building simulated.

Figure 4 Annual cooling and heating load, site, and source energy savings after applying a WR or STGR retrofit to the representative office building.

Figure 5 The 40-year lifecycle NS of a WR or STGR retrofit of the representative office building.

Figure 6 Annual CO_2, NO_x, and SO_2 emission savings per unit conditioned roof area after applying a white roof or garden roof retrofit to the office building prototype.

Figure 7 Comparison of WR and STGR retrofits during 40-year NS in present values for the representative office building in five cities from different Chinese climate zones.



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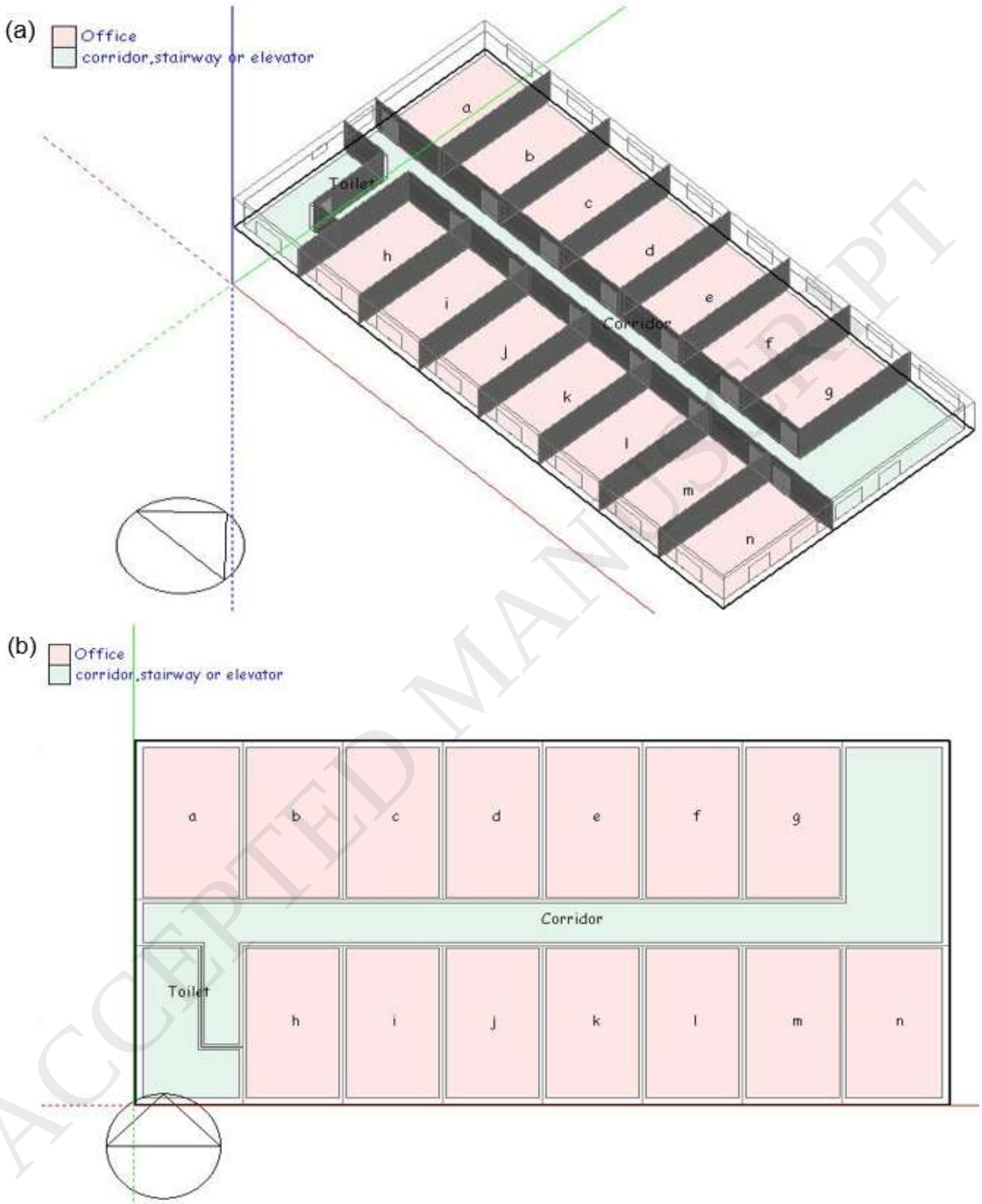

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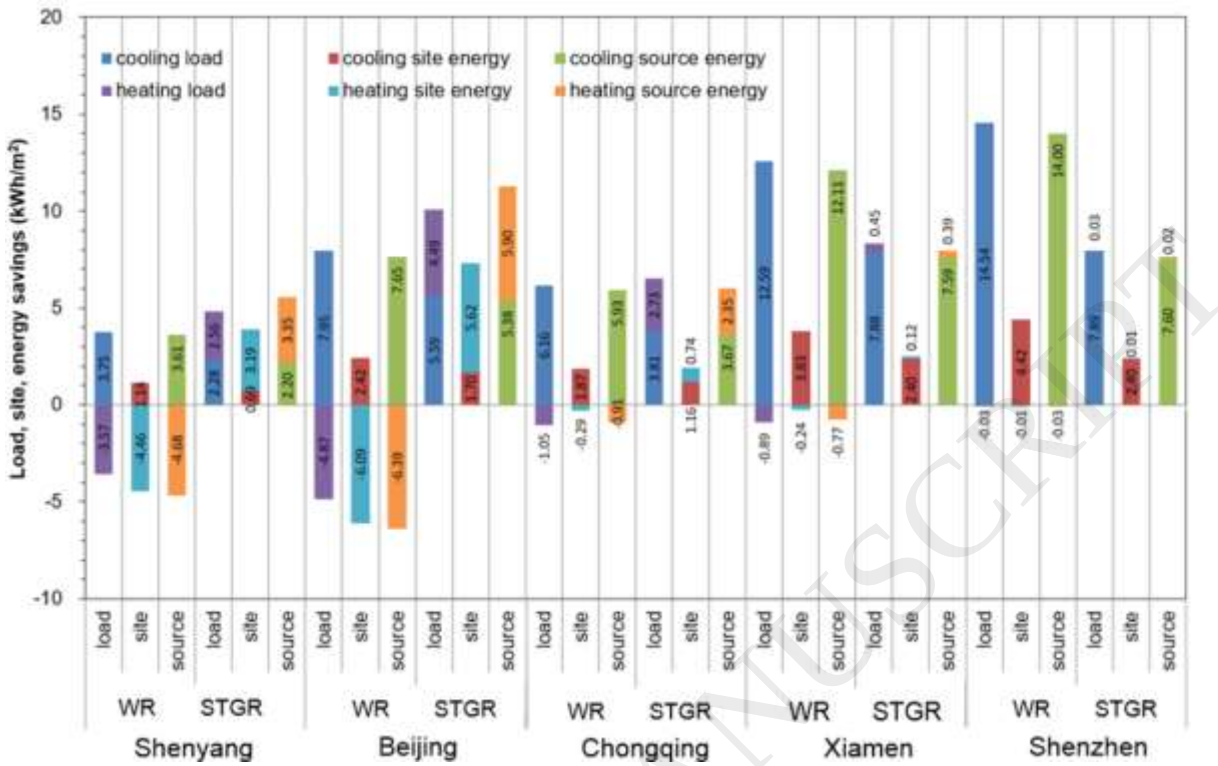

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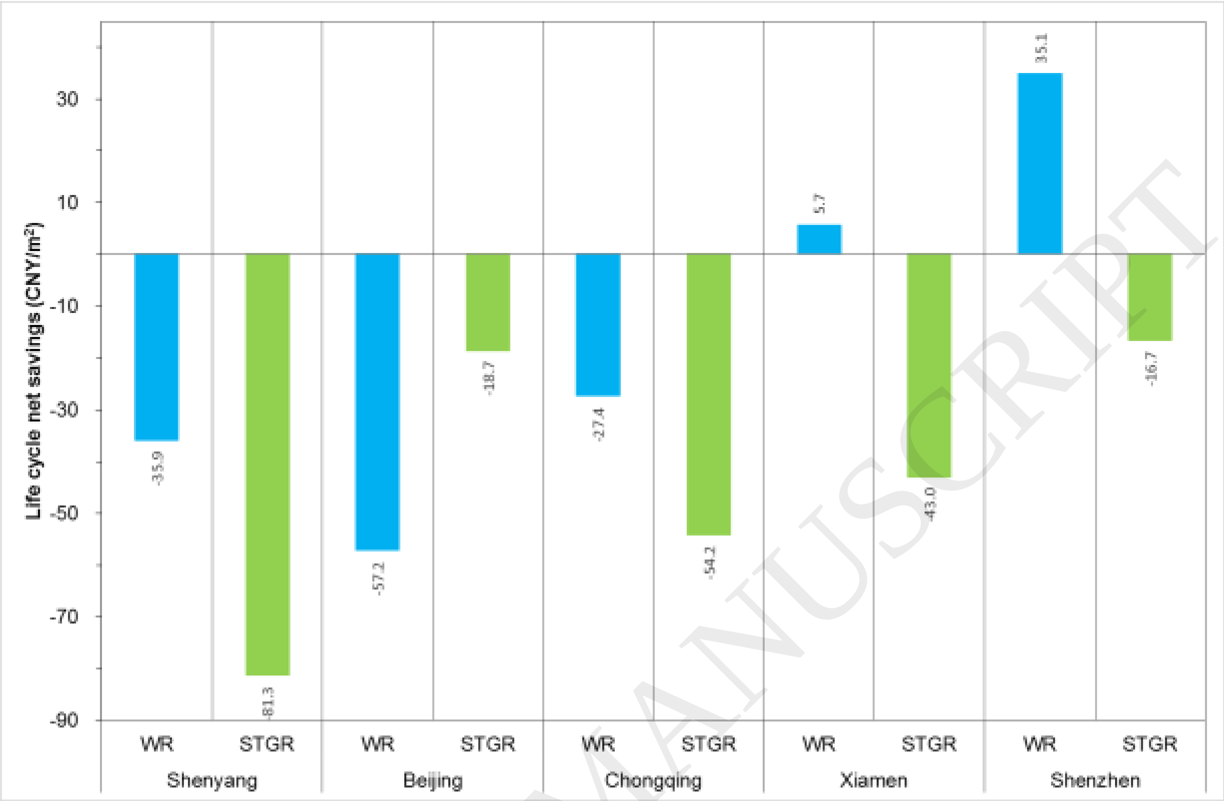

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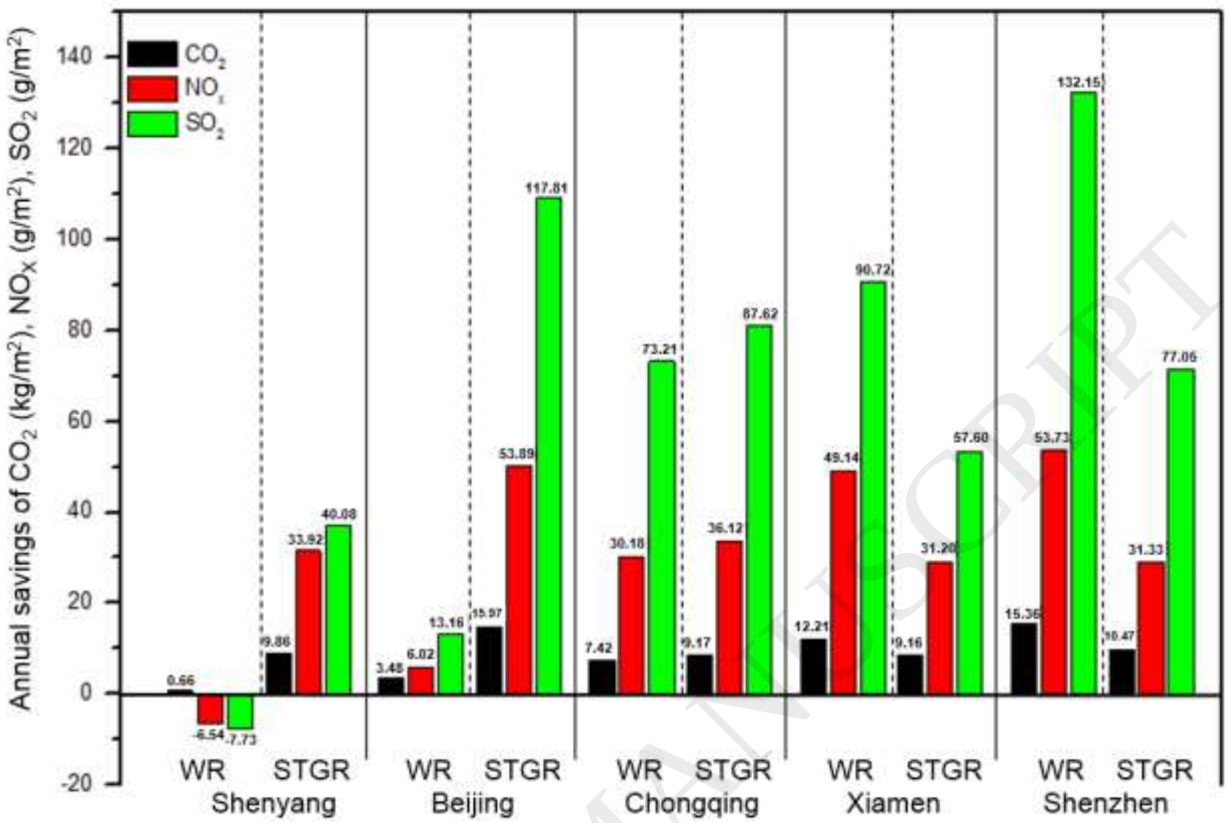

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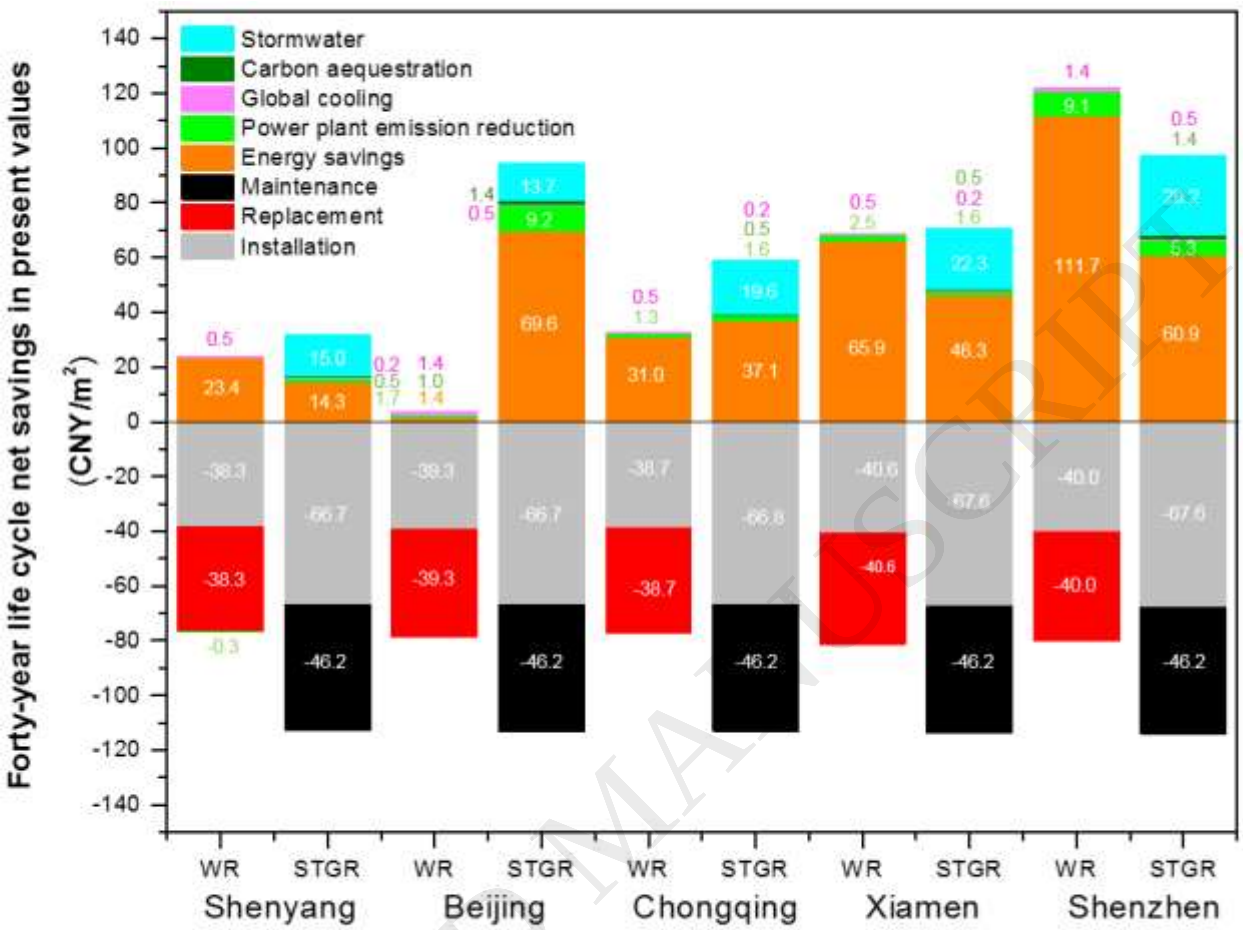

Figure 7. Comparison of WR and STGR retrofits during 40-year NS in present values for the representative office building in five cities from different Chinese climate zones.

Table captions

Table 1 Characteristics of the representative office building simulated.

Table 2 Maximum and set values for the thermal transmittance (W/m^2K) of building envelope components permitted in various Chinese cities.

Table 3 Roof and wall construction (listed outside to inside) of a representative office building in each city.

Table 4 Specifications of Sedum lineare planting modules.

Table 5 Electricity prices (CNY/ kWh) and coal heating prices (CNY/ kWh) in each simulated city.

Table 6 Electricity emissions factors (mass of pollutant emitted per unit non-base electrical energy supplied to the grid).

Table 7 Coal emissions factors (mass of pollutant emitted per unit fuel energy consumed).

Table 8 CO_2 trading prices. The prices in Shenyang and Xiamen were assumed to equal that in Chongqing, which had the lowest price in China as of February 2016.

Table 9 Annual stormwater-related cost savings of STGRs in five cities in China.

Table 10 Default value inputs for life-cycle cost analysis.

Table 1. Characteristics of the representative office building simulated.

Layout	Top floor (office, corridor, stairway)
Conditioned floor area, conditioned roof area (m^2)	285
Story height (m)	3.0
The ratio of window area to wall area	0.21 (south), 0.21 (north)
Building shape coefficient (surface-to-volume ratio) (m^{-1}) [a]	0.26
Roof, wall, window thermal transmittance ($W\ m^{-2}\ K^{-1}$)	See Table 3
Roof construction	See Table 4
Wall construction	See Table 4
Occupant density (person/m^2)	0.25 (office) [b], 0.02 (corridors) [b]
Equipment load (W/m^2)	20 (office) [b], 0 (corridors)[b]
Lighting load (W/m^2)	11 (office)[b], 5 (corridors) [c]
Cooling setpoint (°C)	26, with the setup to 37[b]
Cooling schedule	Weekdays 08:00 – 18:00, excluding holidays [b]
Heating set point (°C)	20, with the setup to 12[b]
Heating schedule	Weekdays 08:00 – 18:00, excluding holidays [b]
Minimum fresh air ventilation (L/s-person)	8.33 [c]
Infiltration (ac/h)	0.75 [d]

[a] Calculated for a three-floor office building.
[b] Suggestion for simulation from [36].
[c] Prescriptive requirement [36].
[d] Suggestion from [37].

Table 2. Maximum and set values for the thermal transmittance (W m^{-2} K^{-1}) of building envelope components permitted in various Chinese cities [33][36][37]38][39][40].

City	Maximum values			Set values in DesignBuilder v4.2		
	Roof	Wall	Window	Roof	Wall	Window
Shenyang	0.45	0.5	3.5	0.38	0.43	3.07
Beijing	0.55	0.6	3.2	0.55	0.58	2.6
Chongqing	0.7	1.0	3.5	0.63	0.92	3.05
Xiamen	0.9	1.5	4.7	0.76	0.82	3.5
Shenzhen	0.9	1.5	4.7	0.63	0.68	3.5

Table 3. Roof and wall construction (listed outside to inside) of a representative office building in each city [40][5].

City	Roof construction	Wall construction
Shenyang	10 mm waterproof layer +30 mm c15 concrete +150 mm Ceramsite + 60 mm expanded polystyrene board + 60 mm boiler slag + 100 mm reinforced concrete + 20 mm cement mortar	80 mm slag concrete polystyrene board + 240 mm concrete perforated brick + 20 mm lime mortar
Beijing	4 mm waterproof layer + 30 mm cement mortar + 50 mm EPS + 55 mm cement perlite + 100 mm reinforced concrete + 20 mm cement mortar	20 mm outer decoration + 50 mm ventilation air layer + 300 mm aerated concrete block + 15 mm inner wall plaster layer
Chongqing	5 mm waterproofing membrane + 20 mm cement mortar + 45 mm EPS + 20 mm cement mortar + 20 mm slag cement + 120 mm reinforced concrete + 20 mm cement mortar	20 mm polymer mortar + 25 mm expanded polystyrene board + 240 mm sintering shale brick + 20 mm lime, cement, mortar
Xiamen	10 mm face brick + 6 mm polymer mortar + 30 mm polyurethane rigid foam + 20 mm waterproofing layer + 30 mm cement mortar + 110 mm reinforced concrete + 25 mm lime mortar	5 mm outer decoration + 5 mm mortar, masonry + 30 mm polystyrene board + 200 mm clay porous brick + 10 mm inner wall plaster layer
Shenzhen	30 mm cement mortar + 50 mm Styrofoam + 30 mm cement mortar layer + 20 mm waterproofing layer + 120 mm reinforced concrete + 30 mm lime mortar	25 mm lime, cement, mortar + 190 mm aerated concrete cement + 20 mm molded polystyrene board + 4 mm plaster plastering pressure grid

[5] C15 means strength grade of concrete

Table 4. Specifications of Sedum lineare planting modules [8].

Item	Value
The height of plants (m)	0.18
Leaf area index (LAI)	2.30
Leaf albedo	0.30
Thermal emittance	0.95
Minimum stomatal resistance (s/m)	100
Max volumetric moisture content at saturation	0.50
Min residual volumetric moisture content	0.01
Initial volumetric moisture content (kg/m^3)	0.15
Conductivity (W/m·K)	0.50
Specific heat (J/kg·K)	1,470
Density (kg/m^3)	600

Table 5. Electricity prices (CNY/ kWh) and coal heating prices (CNY/ kWh) in each simulated city.

	Electricity (CNY/ kWh)	Coal heating[d] (CNY/ kWh)
Shenyang	0.77[a]	0
Beijing	0.86[b]	0.30
Chongqing	0.82[b]	-
Xiamen	0.78[b]	-
Shenzhen	1.08[c]	-

[a] As of December 2018 [46]
[b] As of August 2016 [47][48][49]
[c] As of August 2018 [50]
[d] As of December 2016, building occupants in Beijing pay a flat annual rate for coal heating (CNY/heated floor area) plus a fuel surcharge (CNY/ kWh)[51], while those in Shenyang pay only a flat annual rate (CNY/heated floor area) [52]. Buildings elsewhere are assumed not to use coal heating.

Table 6. Electricity emissions factors (mass of pollutant emitted per unit non-base electrical energy supplied to the grid) from [34].

City	Electricity emissions factor		
	CO_2 (kg/ kWh) [a]	NO_x (g/ kWh) [b]	SO_2 (g/ kWh) [b]
Shenyang	1.12	5.5	6.5
Beijing	1.00	4.3	9.4
Chongqing	0.93	5.4	13.1
Xiamen	0.86	3.9	7.2
Shenzhen	0.92	3.7	9.1

[a] Baseline Emissions Factors for Regional Power Grids in China [53].
[b] SO_2 and NO_x emissions factors of China's national power grids [54].

Table 7. Coal emissions factors (mass of pollutant emitted per unit of fuel energy consumed) from [34].

CO_2 (kg/kWh) [a,b]	NO_x (g/kWh) [a,c]	SO_2 (g/kWh) [a,c,d]
0.3292	0.65	2.7

[a] For sub-bituminous coal, which makes up the largest share (42.6%) of China's accumulated proven coal resources [55] and has an energy content (higher heating value) of 5573 kWh/t [54].
[b] From [11], which notes that coal CO_2 emissions factors are independent of combustion system type and boiler firing configuration.
[c] For a spreader stoker burning sub-bituminous coal (Section 1.1 of [55]).
[d] Assumes coal is 1.06% sulfur by mass [56].

Table 8. CO_2 trading prices. The prices in Shenyang and Xiamen were assumed to equal that in Chongqing, which had the lowest price in China as of February 2016.

City	Price (CNY/ton) [a]
Shenyang	10.4
Beijing	30
Chongqing	10.4
Xiamen	10.4
Shenzhen	29.33

[a] The carbon market in China [58]

Table 9. Annual stormwater-related cost savings of STGRs in five cities of China.

City	Annual precipitation (mm) [a]	Water conservation (t/year)	Stormwater fees (CNY/year)
Shenyang	690.4	0.81	0.65
Beijing	571.8	0.74	0.59
Chongqing	1104	1.06	0.85
Xiamen	1349	1.21	0.97
Shenzhen	1966	1.58	1.26

[a] Major city precipitation of [66].

Table 10. Default value inputs for life-cycle cost analysis.

	Shenyang		Beijing		Chongqing		Xiamen		Shenzhen		Data source
	WR	STGR	WR	STGR	WR	STGR	WR	STGR	WR	STGR	
Installation, replacement, and maintenance (relative to grey)											
Installation cost (CNY/m^2)[a]	38.30	66.70	39.30	66.90	38.70	66.80	40.6	67.60	40.00	67.70	Median value from [38], including labor
Replacement cost (CNY/m^2)	38.30	-	39.30	-	38.70	-	40.6	-	40.00	-	The same to installation cost of WR
Maintenance cost (CNY/m^2·y)	-	2.00	-	2.00	-	2.00	-	2.00	-	2.00	Median value [5][28]
Service life (y)	20	40	20	40	20	40	20	40	20	40	Median value [5]
Energy-related cost savings (relative to grey)											
Coal heating energy savings (kWh/m^2·y)	-4.68	3.35	-6.39	5.90	-	-	-	-	-	-	Simulation results
Heating energy savings (kWh/m^2·y)	-	-	-	-	-0.91	2.35	-0.77	0.39	-0.03	0.02	Simulation results
Cooling energy savings (kWh/m^2·y)	3.61	2.20	7.65	5.38	5.93	3.67	12.11	7.59	14.00	7.60	Simulation results
Energy-related cost savings (CNY/m^2·y)	3.21	1.96	4.05	2.43	4.23	5.06	9.07	5.76	14.38	8.38	Evaluated from energy savings data
Emissions reduction benefits (relative to grey)											
CO_2 emissions reduction (kg/m^2·y)	-1.34	6.97	1.48	13.29	5.42	6.49	10.21	6.48	13.36	7.79	Evaluated from energy source savings
NO_x emissions reduction (g/m^2·y)	-6.54	33.92	6.02	53.89	30.18	36.12	49.14	31.20	53.73	31.33	Evaluated from energy source savings
SO_2 emissions reduction (g/m^2·y)	-7.73	40.08	13.16	117.81	73.21	87.62	90.72	57.6	132.15	77.05	Evaluated from energy source savings
Carbon sequestration benefits (kg/m^2·y)	-	2.00	-	2.00	-	2.00	-	2.00	-	2.00	Median value [5]
CO_2 offset by global cooling (kg/m^2·y)	2.00	0.68	2.00	0.68	2.00	0.68	2.00	0.68	2.00	0.68	Median value [5]
CO_2 emissions related savings (CNY/m^2·y)	0.01	0.10	0.10	0.48	0.08	0.10	0.13	0.10	0.45	0.31	Evaluated from data above
Stormwater-related benefits (relative to grey)											
Stormwater fee cost savings (CNY/m^2·y)	-	0.65	-	0.59	-	0.85	-	0.97	-	1.26	Noted in Section 2.2.4

[a] With some case studies spread over four Chinese climate zones and huge quantities of information available from market research, although the data are clearly inadequate for regional LCCAs, we choose the median value.