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

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

3

4 **ABSTRACT**

5 White roof (WR) and *Sedum lineare* tray garden roof (STGR) have been convinced to
6 improve the energy-efficiency and provide various benefits for conventional impervious grey roofs.
7 Some national and local standards have standardized and recommended these technologies in
8 existing building retrofits, however, they do not include assessment and choice of a particular roof
9 retrofit in different climates. This paper presents a 40-year life-cycle cost analysis (LCCA) of an
10 office building roof retrofitted by adding either WR or STGR over an existing grey roof in five cities,
11 located in four Chinese climate zones. The LCCA find that the WR retrofits exhibit positive life-
12 cycle net savings (NS) in warm winter zones, ranging 5.7–35.1 CNY/m², and STGR retrofits have
13 negative NS of -81.3– -16.7 CNY/m² in all climate zones. The NS of both WR and STGR generally
14 tend to improve as one moves from the coldest cities to the warmest cities.

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

19 **Key Words**

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

21

22 1. Introduction

23 As of 2010 and 2013, China has become the world's largest energy consumer (21% of the
24 global total) and carbon emitter (28% of the global total), respectively [1]. By 2014, 33% of the
25 total energy use and 40% of all CO₂ emissions attributed to the drastic growth of office space to
26 10.7 billion m² in China [2][3]. The energy consumption of office buildings (excluding heating)
27 leads all building types [4]; this contributes to global warming and the summer urban heat island
28 (UHI) effect, and results in heat-related deaths, peak-hour power demand increases, and other
29 ecologically adverse impacts [5]. In response to the current energy usage situation, the Chinese
30 government is comprehensively promoting the energy savings and green retrofitting of existing
31 office buildings during the "13th Five-Year Plan" period [6].

32 The solar reflectance change of urban surface attribute to the rapid urbanization on building
33 sectors and environments creates a significant difference in the air temperatures of cities versus
34 their countryside. Conventional impervious grey roofs in China (with an albedo of about 0.10 to
35 0.20) absorb roughly 80% of solar infrared radiation portion of which is dissipated to heats the
36 roofs and atmosphere, increasing the cooling costs of air conditioning systems, and heightening
37 the effects of global warming and UHI [7]. High albedo (solar reflectance) white roof (WR) or
38 sedum-lineare garden roof (STGR) are commonly considered to mitigate the detrimental effects
39 associated with grey roofs [5][8].

40 The selection of WR (albedo of 0.55–0.90) can reduce the heat gain of a structure,
41 consequently reducing the cooling load in a conditioned space [9], Levinson et al. [10] reported
42 annualized cooling site energy savings measured about 0.6–6.4 kWh/m² from several WR retrofits
43 in the United States (U.S.). However, boosting the albedo of roof surfaces can also result in higher
44 heating costs, referred to as the winter heating penalty, especially in cold climates [11].
45 Simulations of WRs on commercial buildings across the U.S. determined that the energy cost
46 savings varied with climate zones. Savings in Hawaii (Aw-tropical wet/dry season climate,
47 \$1.14/m²·y) were generally greater than those in Minnesota (Dfb-humid continental climate,

48 \$0.13/m²·y)—except in Alaska (\$0.32/m²·y), where annual energy cost savings were enhanced
49 by the low price of heating gas and high price of electricity for cooling [10].

50 Raising roof albedo also mitigates the summer UHI and provides “global cooling” by
51 reducing solar heating of the atmosphere, which can reduce the carbon emission and provide
52 environmental reliance and sustainability [12]. Akbari et al. [13] conducted simulations increasing
53 the albedo of urban locations on the basis of two independent estimates of the spatial extent of
54 urban areas and found the resulting global cooling effect ranged 0.01–0.07 K, corresponding to
55 an equivalent one-time reduction in CO₂ emissions of 25–150 billion tons.

56 Garden roof can provide evaporative cooling as well as effective thermal insulation, thereby
57 providing year-round energy savings [8]. Garden roofs offer little, if any, global cooling potential
58 because the albedo typically ranges 0.16–0.26 [14], and the cool moist air above the garden
59 surface eventually condenses as rain, releasing heat [15]. Garden roofs also offer other
60 environmental benefits relative to WR, including UHI mitigation, stormwater control, air quality
61 improvement, and biodiversity; they also provide recreational, agricultural, and landscape value
62 to the community [16]. Stormwater management is widely considered as an important benefit of
63 garden roofs. Tang [17] estimated that a 100 mm soil layer in a garden roof can hold water of
64 approximately 16–22 mm. Adams et al. [18] investigated saving 35% of the original stormwater
65 fee (\$0.90/m²·y) in Portland, Oregon by installing a garden roof.

66 Previous studies on the conventional garden roof have found that garden roofs justified
67 sustainable construction product due to their environmental benefits, but compete for their cost
68 disadvantage in building budgets [19]. Peng et al. [20] estimated that extensive garden roofs have
69 a positive net savings of \$10.8/m²·y in Hong Kong, while Sproul et al. [5] estimated that extensive
70 garden roofs have a negative 50-year net savings of \$71.0/m² in the U.S. because of the high
71 initial costs and insurance premiums. The high costs of extensive roofs also make the government
72 and individuals hesitant to promote garden roofs [5]. Compared with a common garden roof,
73 sedum-tray garden roof (STGR) mainly consists of sedum-tray trays which can be placed on top

74 of the waterproofing protection layer and connected to drains (Figure 1). Therefore, the light-
75 weight and modularized STGR which offers low installation cost and easy maintenance thrives in
76 a variety of climates have been launched into the market [8][21] The advantages of the STGR
77 system have been recognized in engineering practice [8]. In this study, STGR is studied from an
78 economic perspective.

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

80 In general, to reduce the environmental damage created by grey roofs, WR and STGR are
81 implemented widely to achieve energy savings with strategic environmental, economic, and social
82 benefits [22]. However, although the lifecycle assessment is applied to quantify and improve this
83 sustainability in construction, a lifecycle benefit-cost value representing a unit of area
84 comparisons among these three roofing systems are still limited, most previous life-cycle cost
85 analyses have focused on a single climate zone, or a single roofing system. There have been
86 some studies conducted to compare the economic benefits between grey roofs and white roofs
87 [10][23][24][25][26] or green roofs [16][27], and these studies almost focus on specific energy
88 efficiency [28], environmental benefits [29][30], life-cycle analysis [5][31], and social cost-benefits
89 [16], respectively. Therefore, with the absence of systematic comparative study on the life cycle
90 assessment of STGR and WR retrofits in all Chinese climate zones, it is difficult to provide a
91 reference for the choice and promotion of existing office building roof retrofits in different climates,
92 the guidelines and standard protocol for the selection of roof retrofit systems to suit a particular
93 climate zone have not been clearly established to date.

94 In this paper, DesignBuilder v5.3, a front end to the EnergyPlus building energy model
95 (EnergyPlus 8.6), is used to simulate the annual conditioning (both heating and cooling) energy
96 savings of a building model based on a representative office building. Using the results of this
97 simulation, a 40-year life-cycle cost analysis (LCCA) is conducted to provide an economic
98 comparison of the cost-effectiveness of retrofitting a roof with WR and STGR systems for cities in

99 four distinct climate zones in China, and provides policy recommendations based on this analysis.
100 This study can bridge the gap in understanding observed in the current literature by quantifying
101 the abstract, scatter environmental benefits of these technologies into proper lively, imaging, and
102 comprehensive economic values, thus providing a set of scientific criteria to aid building managers
103 and planners in selecting environmentally friendly roofing systems for new and existing buildings.

104 **2. Materials and methodology**

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

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

118 We considered two cities (Xiamen and Shenzhen) in HSWW because Gao et al. [34] have
119 ensured that WR can save energy in both HSCW and HSWW in China as the heating loads in
120 those climate regions are quite low. Moreover, the Xiamen and Shenzhen Municipal Government
121 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.

122 2.1. Simulations

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

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

132 Table 1. Characteristics of the representative office building simulated.

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

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

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

138 The HVAC system was designed based on Chinese building energy efficiency standards
139 and is also detailed in Table 1 and Table 2. The occupancy hours were set as 08:00–18:00 local
140 standard time from Monday to Friday, excluding holidays. The setpoint temperature was 26 °C in
141 summer and 20 °C in winter. Space cooling was provided by a split direct expansion air-source
142 heat pump with a cooling coefficient of performance (COP) of 3.2, which is typical in China [34].
143 The heating system was determined by the climate zone: a coal-fired boiler with an efficiency of
144 80% was used in severe cold and cold zones, while the same air-source heat pump (heating COP
145 of 2.8) used for air cooling was used for heating in the other two climate zones.

146 The building model was simulated with three different roofs. The grey roof (with an aged
147 albedo of 0.20) was used as the reference roof. The WR system used consisted of a white

148 elastomeric coating (aged albedo of 0.60) installed on top of a grey roof, while the STGR system
149 was made of *Sedum lineare* planting modules with the values described in Table 4.

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

154 **2.2. Life-cycle cost analysis**

155 A 40-year LCCA was conducted to determine the NS for an office building roof retrofitted
156 with a WR or STGR system in the target cities spread through four Chinese climate zones. Some
157 previous works indicate that the use of a garden-roof is expected to last for more than 40 years
158 compared to 20 years for a white membrane roof or a grey roof, made up with a concrete and
159 waterproof layer [5]. Various studies in the U.S. have found that the WR has a service life of 15–
160 20 years [41], and managers typically prefer to just to replace the roof surfacing material at the
161 end of its service life, rather than continuously maintain the roof [8]. Our 40-year LCCA includes
162 at least once replacement cost for the WR, and this study assumes that roof is made white
163 according to *Technical specification for application of architectural reflective thermal insulation*
164 *coating JGJ/T359-2015*, after applying 2–3 layers of architectural thermal insulation reflective
165 coating (each layer ≥ 2 mm) over an existing grey roof, then a white waterproof layer is specified.

166 The analysis includes the installation, replacement, and maintenance costs of the roofs;
167 energy cost savings (simulated for both cooling and heating); reduction in emissions of CO₂, NO_x,
168 and SO₂ from power plants and increase in emissions from coal furnace in cold zone; equivalent
169 CO₂ emissions reduction from carbon sequestration and global cooling; and the stormwater
170 control benefits. Following Sproul et al. [5], we note that other benefits of these roofing systems,
171 including biodiversity, aesthetic value, and increased property value can be difficult to quantify,
172 and are thus not taken into account in this study.

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

$$178 \quad NPV = \sum_{i=1}^{40} \frac{(C_i - C_0)}{(1+r)^i} \quad (1)$$

179 where C_i is the annual profit of the WR or STGR compared to grey roof including energy
180 cost savings, carbon emissions reduction savings, and stormwater-related savings, in CNY/m²·y;
181 C_0 is the annual cost including installation, maintenance costs (STGR), and replacement costs
182 (WR), in CNY/m²·y; the real (inflation-adjusted) annual rate of return r is set to 3% [42]; and the
183 number of years in the life cycle is set to 40.

184 **2.2.1. Installation, replacement, and maintenance costs**

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

191 White roofs are widely known as an affordable and simple alternative to grey roofs. The
192 costs of the coating itself can be quite different depending on the specifications, type, and
193 manufacturer selected for use. Over its service life, the most expensive thermoplastic elastomeric
194 membrane (\$20/m²) could be \$7.4/m² cheaper than installing the cheapest built-up bituminous
195 roofing in some cases [5], while the median market price (materials) of white coating in China is
196 approximately 36.3 CNY/m² (\$5.48 /m²) [43]. Compared to common extensive garden roofs with

197 installation costs of \$108–248/m² [44], STGR enjoys a considerable cost advantage at about
198 \$10.4/m² installation cost², which yields only 10% of extensive garden roofs above [43].

199 A routine maintenance cost of 1.34 CNY/m²·y (\$0.20 /m²·y) required including repair leaks
200 and cleaning gutters/downspouts [5]. Corresponding maintenance costs occur in the grey roof,
201 WR, and STGR systems, that is, there is no additional maintenance cost of WR compared to the
202 grey roof. However, additional maintenance needs of STGRs, including simple irrigation, costs
203 2.00 CNY/m² [28], or about 10 % of the median of the 40-year maintenance cost of an extensive
204 green roof (\$2.90 /m²·y) [5]. While a common extensive green roof has its drainage layer under
205 the soil, the drainage layer of an STGR is located in the bottom of the container and can be easily
206 installed, cleaned, and repaired (see Figure 1). To accomplish these maintenance tasks, laborers
207 are required to perform a minimum of three visits per year.

208 **2.2.2. Heating and cooling site energy and source energy cost savings**

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

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

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

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

223 **2.2.3. Power plant emissions savings and CO₂ emissions trading price**

224 The CO₂, NO_x, and SO₂ emissions reductions from heating or cooling energy savings were
225 calculated by dividing the heating and cooling source energy savings by the appropriate energy
226 transmission efficiency and pollutant emissions factors (Table 6, 7), as shown in Eq. (2), and then
227 summed to yield the emissions savings for each pollutant ($i = \text{CO}_2, \text{NO}_x, \text{and SO}_2$). That is,

$$228 \quad M_i = \frac{E \times k_i}{\eta} \quad (2)$$

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

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

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

236 As of February 2017, carbon trading markets exist in seven provinces and cities in China:
237 Guangdong province, Hubei province, Shenzhen city, Beijing city, Shanghai city, Tianjin city, and
238 Chongqing city. Although Shenzhen is part of Guangdong, it has its own carbon trading market.
239 The carbon trading market was extended throughout China by 2016 [56]. Table 8 shows the
240 lowest carbon trading price in each considered location. We observe that the carbon price in
241 China is about one-thirtieth that in Europe [57]. Notably, though the current work calculates the
242 value of carbon savings, the LCCA omits the values associated with NO_x and SO₂ savings as
243 these emissions are yet not traded in China.

244 Table 8. CO₂ trading prices. The prices in Shenyang and Xiamen were assumed to equal
245 that in Chongqing, which had the lowest price in China as of February 2016.

246 The annual equivalent CO₂ emissions reduction from carbon sequestration is given by the
247 median of the reported data as 1.23–2.48 kg/m² [59]. Moreover, Sproul et al. [5] compared white
248 roofs (aged albedo of 0.60) and garden roofs (aged albedo of 0.20) to black roofs (aged albedo
249 0.05–0.10) and found the global cooling benefits of WR cause by CO₂ emission reduction only
250 apply to the first 40-year life-cycle, yielding emissions reduction benefits of 2.00 kg/m² and 0.68
251 kg/m², respectively.

252 **2.2.4. Stormwater-related benefit**

253 As an integral part of the urban ecosystem, an STGR can be an effective savings of a
254 building stormwater management plan, because the canopy and substrate can capture and store
255 the outflow of water. This paper estimates the water conservation in the canopy and substrate by
256 the method of water balance [60], then applies sewage treatment charges based on 227 samples
257 in China (median of 0.8 CNY/t) [61] to determine stormwater-control cost savings. It is assumed
258 the use of an STGR reduces the annual stormwater fees (Table 9) [62] comes from the annual
259 transpiration water (about 0.39 t/m²) [63] and water conservation (at least 61.5% of runoff) effects
260 [64].

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

262 **3. Results**

263 **3.1. Annual air conditioning load, site energy, and source energy savings**

264 Raising the roof albedo to 0.60 (aged WR) from 0.20 (aged grey roof) decreases the annual
265 cooling load by 1.14–3.75 kWh/m², annual cooling site energy use by 3.61–14.00 kWh/m², and
266 annual cooling source energy use by 3.75–14.54 kWh/m² (where Shenyang < Chongqing <
267 Beijing < Xiamen < Shenzhen), respectively. It also increases the heating load by 0.01–4.46
268 kWh/m², annual heating site energy by 0.03–4.68 kWh/m², and annual heating source energy by
269 0.03–3.57 kWh/m² (where Shenzhen < Xiamen < Chongqing < Shenyang < Beijing), respectively.

270 Adding the sedum trays to the grey roof decreases the annual cooling load by 2.28–7.89
271 kWh/m², annual cooling site energy use by 0.69–2.40 kWh/m², and annual cooling source energy
272 use by 2.20–7.60 kWh/m² (where Shenyang < Chongqing < Beijing < Xiamen < Shenzhen),
273 respectively. It also decreases the heating load by 0.03–4.49 kWh/m², annual heating site energy
274 by 0.01–1.70 kWh/m², and annual heating source energy by 0.02–5.90 kWh/m² (where Shenzhen
275 < Xiamen < Chongqing < Beijing < Shenyang), respectively (see Figure 4).

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

278 Some results from previous studies referred to ensure the validity of our results. Gao et al.
279 [34] conducted the energy consumption measurement case studies including the WR and grey
280 roof in office buildings in Chongqing (HSCW) in 2012, the air conditioner in test room with WR
281 saved about 0.05 kWh/m²·d less electricity than that in room with grey roof in cooling season, and
282 energy savings of WR reported the cooling energy savings in Beijing and Chongqing decreased
283 by WR ranged 1.65–1.59 kWh/m², as opposed to -5.85–0.30 kWh/m² of heating energy savings,
284 respectively. These measurement and calculation results are similar to the simulation results in
285 this paper. And in 2015, a WR, grey roof and STGR were applied to the three unoccupied air-
286 conditioned top floor rooms of an office building in Guangzhou (near Shenzhen, HSWW). The
287 annual cooling energy savings of WR and STGR can be calculated about 4.86 kWh/m² and 3.60
288 kWh/m², respectively [66]. Although we found the measurement results were 0.44 kWh/m²
289 and 1.20 kWh/m² greater than corresponding calculated results of WR and STGR, we believe the
290 calculation results are reasonable agreement for an aged WR and STGR, because the WR and
291 STGR applied to the tested rooms were just finished on May 2015, and the tested rooms were
292 unoccupied without any plug loads, while the calculated models were on-use with occupancy,
293 lighting, and other equipment.

294 **3.2. Economic comparison of WR and STGR retrofits**

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

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

301 Figure 5 shows the life cycle NS when using WR and STGR in each case. Excluding the
302 economic value of SO₂ and NO_x emissions savings, the following findings can be stated:

303 (1) The cost-effectiveness³ of both WR and STGR tend to improve as one moves from the
304 coldest cities to the warmest cities (left to right in Figure 5), excepting Beijing.

305 (2) The 40-year lifecycle NS for the WR retrofits ranged from -35.9 CNY/m² (Shenyang, SC)
306 to 35.1 CNY/m² (Shenzhen, HSWW), and the results across the five cases are greater than the
307 differences. The WR exhibits poor cost-effectiveness in SC, C, and HSCW; however, the cost-
308 effectiveness of a WR system in HSWW is much more advantageous. The winter heating penalty
309 of a WR increases the energy costs in cold winter areas and results in poor cost-effectiveness. In
310 HSWW, however, the heating load and demand are low, and as a result so are the negative
311 effects of WR usage.

312 (3) The 40-year NS of STGR retrofits ranged from -81.3 CNY/m² (Shenyang, SC) to -16.7
313 CNY/m² (Shenzhen, HSWW) (see Figure 5), indicating that the use of an STGR offers poor cost-
314 effectiveness in China, lower than that of a WR in every climate zone evaluated.

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

³ Positive NS during 40-year lifecycle.

317 50-year NS of white roof (\$25 /m²), and a negative NS of green roof (-\$71 /m²) in a study of 22
318 cases in the U.S.

319 Figure 6. Annual CO₂, NO_x, and SO₂ emission savings per unit conditioned roof area after
320 applying a white roof or garden roof retrofit to the office building prototype.

321 It is important to note that some default values were used in these calculations for values
322 such as the CO₂ emissions reduction from carbon sequestration and global cooling benefits. Also,
323 the cost savings of SO₂ and NO_x emissions reductions, which cannot be evaluated without
324 nitrogen and sulfur trading mechanisms, were ignored. Thus, the results of this analysis will
325 change as more real-world data can be included.

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

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

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

336 **3.2.1. Roof installation and maintenance costs**

337 As shown in Figure 7, because a WR has to be replaced once during the 40-year life cycle
338 analysis period, a WR has higher installation cost premiums than an STGR. The installation cost
339 difference is relatively modest, ranging from 9.9–13.6 CNY/m² (Table 10, lines 1 and 2). Moreover,
340 a present value of the maintenance cost over the 40 year life-cycle for an STGR is 46.2 CNY/m².

341 **3.2.2. Energy cost savings**

342 Generally, the 40-year lifecycle NS of WR and STGR are illustrated to increase
343 monotonically when one moves from the coldest city to the warmest city (left to right in Figure 5),
344 as well as the roof thermal transmittance U increase (Table 1). However, the deviation of Beijing
345 results from the general trend is depicted largely due to the influence of energy cost savings which
346 was the lowest of 1.40 CNY/m² (Figure 7), as the U of Chongqing (0.63 W/m²•K) is higher than
347 that in Beijing (0.55 W/m²•K), and the lowest average monthly temperatures for C (-5°C) are 10°C
348 lower than those in HSCW, the heating site penalties of WR in C are 5.80 kWh/m² bigger than
349 those in HSCW (Figure 4), which lead to more annual energy consumption of 3.67 kWh/m² in C,
350 as opposed to annual energy savings of 1.58 kWh/m² in HSCW (Figure 4). Moreover, another
351 factor such as the price of energy may also be playing a part, as the low price of coal heating and
352 the high price of electricity for cooling in C results in higher energy cost savings in SC than in C
353 (Table 5). These results are similar to those of simulations of energy cost savings in different
354 climates conducted by LBNL in the U.S. [67].

355 With regard to STGR, due to the additional evapotranspiration cooling provided in summer
356 and the heating penalty eliminated by thermal insulation of sedum-tray module in winter (Table
357 10), the annual energy savings exceed others at 7.32 kWh/m², thus the energy cost savings was
358 highest at 69.6 CNY/m² in Beijing (C). Additionally, the cooling load is dominant and heating load
359 is low in HSWW; thus a WR saves 0.85-2.19 CNY/m²•y more in energy costs than an STGR as a
360 result of its higher albedo.

361 **3.2.3. CO₂ emissions trading savings**

362 Carbon emissions reduction comprises power plant emissions reductions, the global cooling
363 benefit included only in the first 40-year life cycle, and the equivalent CO₂ sequestered by the
364 garden roof during its service life (see Figure 6).

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

367 6), the energy cost savings are still positive in both locations, and even greater in SC than in C
368 because office buildings in Beijing were assigned coal heating. The ratio of source energy savings
369 to heating load savings (f/C_h)⁴ of coal heating is 1.5, higher than that of an electric heat pump
370 (0.9), magnifying the heating source energy penalties paid when using a WR and the heating
371 source energy savings realized when using an STGR.

372 The CO₂ emissions savings from the WR retrofit were negative for cities in SC, which was
373 the result of negative coal heating savings. As discussed in Section 2.2.4, WRs have greater
374 global cooling benefits than garden roofs because the albedo of a WR is up to three times that of
375 a garden roof. However, an STGR also provides carbon sequestration, which yields a modest life-
376 cycle cost savings of 0.02–0.1 CNY/m². As noted by Gao et al. [34], coal CO₂ emissions factors
377 are independent of the combustion system type and boiler firing configuration [68], but the coal
378 NO_x and SO₂ emissions factors used here are for spreader stokers characterized by the U.S.
379 EPA [69] and may or may not represent actual building furnaces in China. Taking into
380 consideration all the parameters discussed above, the life-cycle value of CO₂ emissions trading
381 savings from an STGR is about 0.69–2.84 CNY/m² less than that of a WR.

382 **3.2.4. Stormwater-related benefits**

383 Savings from avoiding stormwater-related costs are a major benefit of an STGR, the savings
384 value is decided by garden-roof types and local precipitation. The growth medium of the STGR
385 retains water which is later evaporated (approximately 0.39 t/m²·y). The extra stormwater
386 retention capability of the STGR results in an NS of 9.6–15.2 CNY/m², which is much higher in
387 southern cities due to their abundant precipitation. The stormwater-fee cost savings resulting from
388 the use of an STGR, therefore, offers an additional advantage. Additionally, Sproul et al. [5] found
389 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.

390 downsizing results in a cost savings of \$36.0 /m², the benefits occurred just in new buildings or
391 major reconstruction, and excluded in this case of roof retrofit.

392 **4. Discussion**

393 **4.1. Choice of roof retrofit**

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

402 Additionally, the WR retrofits offer poor cost-effectiveness in SC and C result from winter
403 heating penalty, and in HSCW. Gao et al. [34] suggested that WR should be prescribed in building
404 energy efficiency standards for HSCW in China because of WR on office building yields source
405 energy savings of 4.1–10.2 kWh/m²·y in HSCW and HSWW. Although the energy simulation finds
406 the similar energy savings of 5.0 kWh/m²·y in this study, the LCCA results indicate the annualized
407 cost premiums for WR is 0.88 CNY/m²·y in such climate zone where its energy cost savings
408 cannot surpass its cost. In case continued use of grey roofs in HSCW and HSWW will result in
409 increased incidence of heat waves, risking citizen lives, decision makers there should be focused
410 on promoting the use of WRs to realize their increased energy cost savings (shown in Table 10)
411 and global cooling effect, accepting the small annualized premium as a worthwhile cost. It is
412 recommended that new construction or waterproofing replacement, consider the use of WR,
413 which provides many positive benefits at no additional cost to new construction [44].

414 The LCCA results also indicate STGR system is less cost-effective than the WR system.
415 Compare to STGR, WR offers an NS of 26.8–51.8 CNY/m² (see Figure 5). The annualized cost

416 premium is just 0.67–1.29 CNY/m², and much less than those of conventional green roof in the
417 U.S. (\$2.0–4.0/m²) because of the relatively small initial costs [5]. There are deviations regarding
418 the results, the STGR retrofit in Shenzhen (HSWW) (Figure 5) had a negative NS of 16.7 CNY/m²,
419 while Peng et al. [20] simulated large-scale green-roof installation in Hong Kong (close to
420 Shenzhen), and found a substantially positive NS of \$10.8 /m². Possible reasons for this
421 observation are: (1) lower carbon price (67.2 CNY/t in Hong Kong compared with 29.33 CNY/t in
422 Shenzhen) results in lower carbon emission reduction in Shenzhen; (2) lower energy savings
423 (7.62 kWh/m²·y in Shenzhen compared with 48.0 kWh/m²·y in Hong Kong) yielded lower energy
424 cost savings; (3) district-scale extensive roof simulation presents much more savings of 3.31
425 USD/m²·y from UHI mitigation [20], compared with median value of \$0.80 /m²·y in other literature
426 [16][23][26][27][29]. Therefore large-scale garden-roof installation can increase the cost-
427 effectiveness of one garden-roof therein. Besides, the negative NS of STGR underestimates its
428 true social advantages, including some health and aesthetic benefits that cannot be easily
429 monetized.

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

438 **4.2. Policy implications**

439 Since 2014, local energy efficiency standards in several southern provinces, such as in
440 Hainan, Guangzhou, and Shanghai, have proposed credits for use of cool roofs and walls, or use
441 of roof and wall vegetation, in public buildings [70]. Some national and local standards have

442 standardized and recommended the WR and STGR, but not require, assess and choice of a
443 particular roof retrofit in different climate zones. The Research Institute of Standards and Norms
444 of MOHURD is now compiling *General Specification for Building Energy Efficiency & Renewable*
445 *Energy Consumption* and *General Specification for Existing Building Envelope Retrofit* [71]. This
446 presents opportunities to offer the following proposals:

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

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

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

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

465 **5. Conclusions**

466 This paper conducted a life-cycle cost analysis on an office building roof retrofit by
467 simulating the addition of a WR or STGR to the existing grey roof of a representative office

468 building, concluding that the choice between a WR and STGR retrofit depends on the climate
469 zone, local initial investment, operating and maintenance costs, as well as various environmental
470 benefits. This analysis provides valuable reference and policy implications for policy makers by
471 performing the first empirical comparison between the performances of these roofing systems in
472 the different climate zones of China.

473 An economic comparison over a 40-year lifecycle indicates that substituting both an aged
474 WR (albedo 0.60) and an STGR tends to improve as one moves from the coldest cities to the
475 warmest cities, except for Beijing. The WR exhibits cost premium ranged from -57.2 CNY/m² to -
476 27.4 CNY/m² in the central and northern areas of China (C > SC > HSCW), whereas the WR
477 retrofits are certainly economical in HSWW (5.7 CNY/m² in Xiamen and 35.1 CNY/m² in
478 Shenzhen). Meanwhile, a negative NS of STGR retrofits ranged from -81.3 CNY/m² (Shenyang)
479 to -16.7 CNY/m² (Shenzhen), indicating that the use of STGR is not cost-effective. However, the
480 annualized cost premiums are just 0.4-1.1 CNY/m² in HSWW, this annual difference is relatively
481 small.

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

488 The latest national and local energy efficiency standards, such as in Guangdong, Shanghai,
489 Beijing, Jiangsu and Chongqing, standardize and credit WR and STGR retrofits for office buildings
490 with grey roofs, however, they do not include assessment and choice of a particular roof retrofit
491 in different climates. LCCA results suggest adding new building codes concerning crediting or
492 prescribing WR and STGR retrofits into office buildings with grey roofs in hot summer climates
493 (HSCW and HSWW) and HSWW in China, respectively. While current national energy efficiency

494 standard and some local standards in HSWW, such as Hainan, neither credit nor recommend
495 STGR for office buildings. Furthermore, the current aging rating system in Chinese standards,
496 especially in terms of artificial weathering index, lags far behind the Energy Star (ES) and Cool
497 Roof Rating Council (CRRC) in the US.

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678

679 **Figure captions**

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

681 Figure 2 Chinese climates zones and cities.

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

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

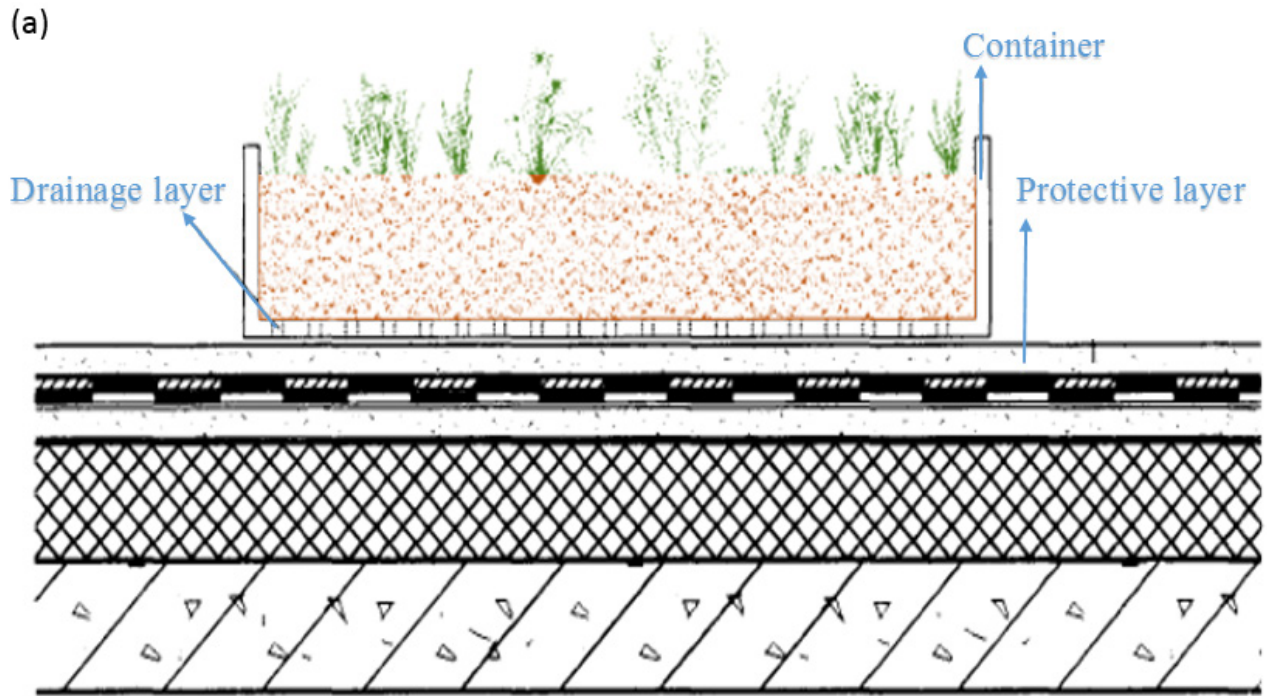
686 Figure 5 The 40-year lifecycle NS of a WR or STGR retrofit of the representative office building.

687 Figure 6 Annual CO₂, NO_x, and SO₂ emission savings per unit conditioned roof area after applying a
688 white roof or garden roof retrofit to the office building prototype.

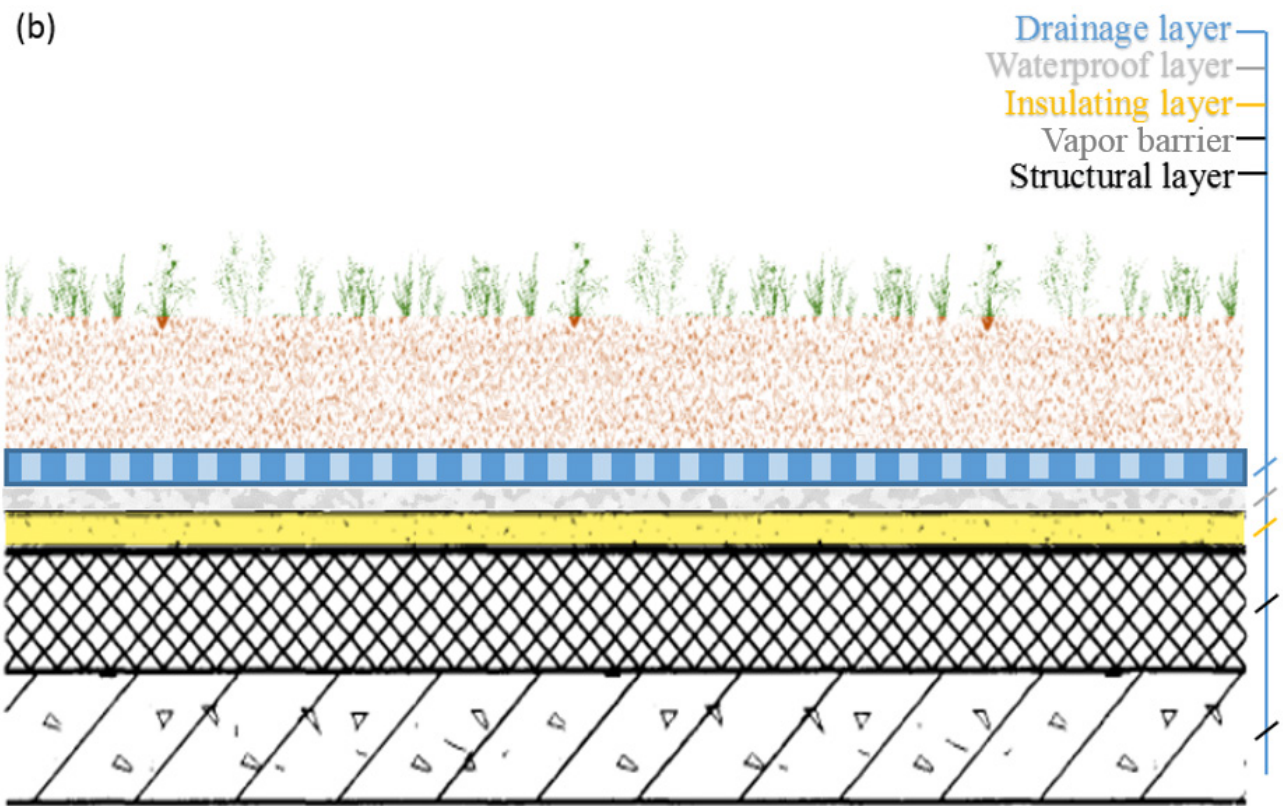
689 Figure 7 Comparison of WR and STGR retrofits during 40-year NS in present values for the representative
690 office building in five cities from different Chinese climate zones.

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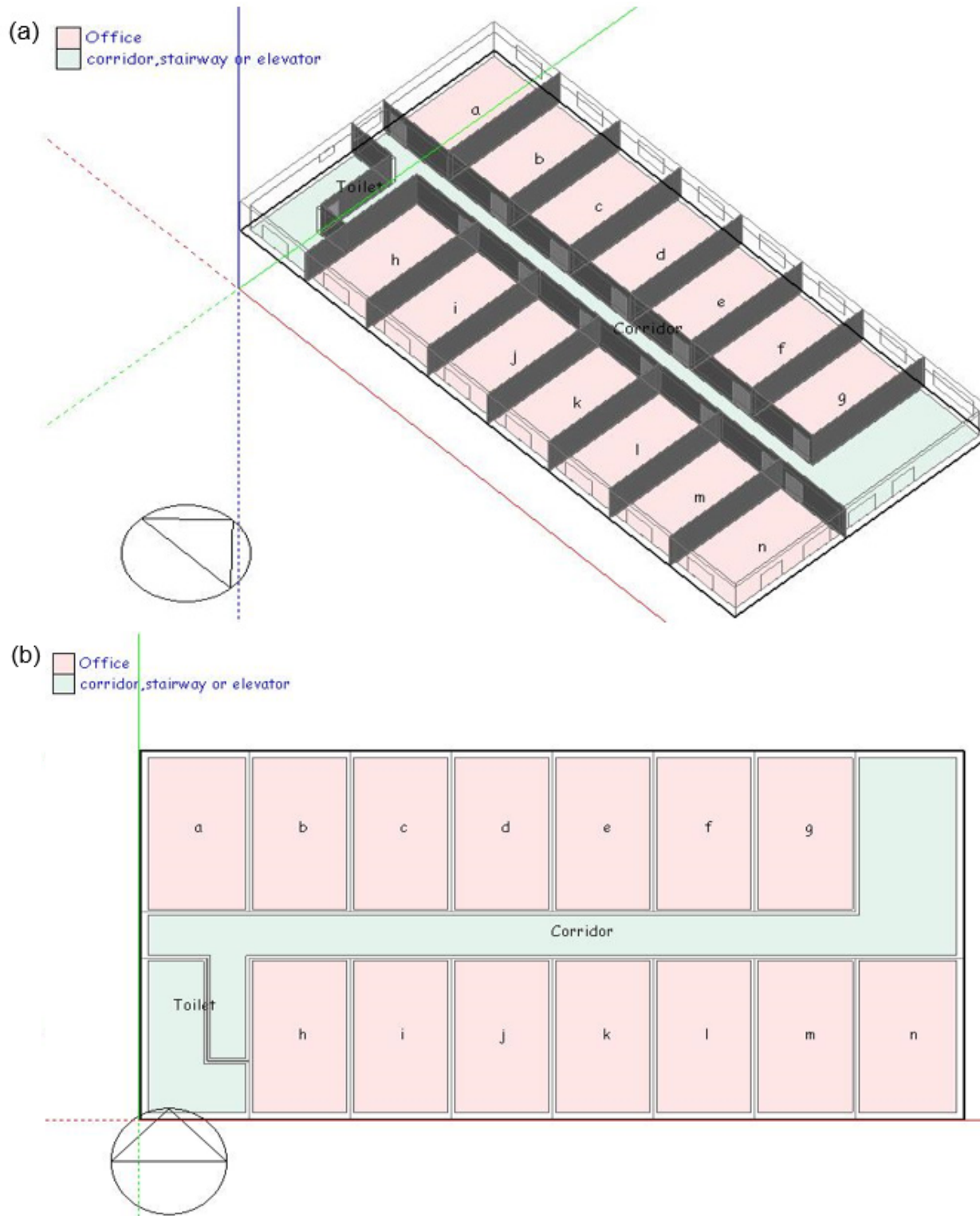
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Figure 1. Structure diagram of (a) an STGR, and (b) a common extensive green roof.



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Figure 2. Chinese climates zones and cities.



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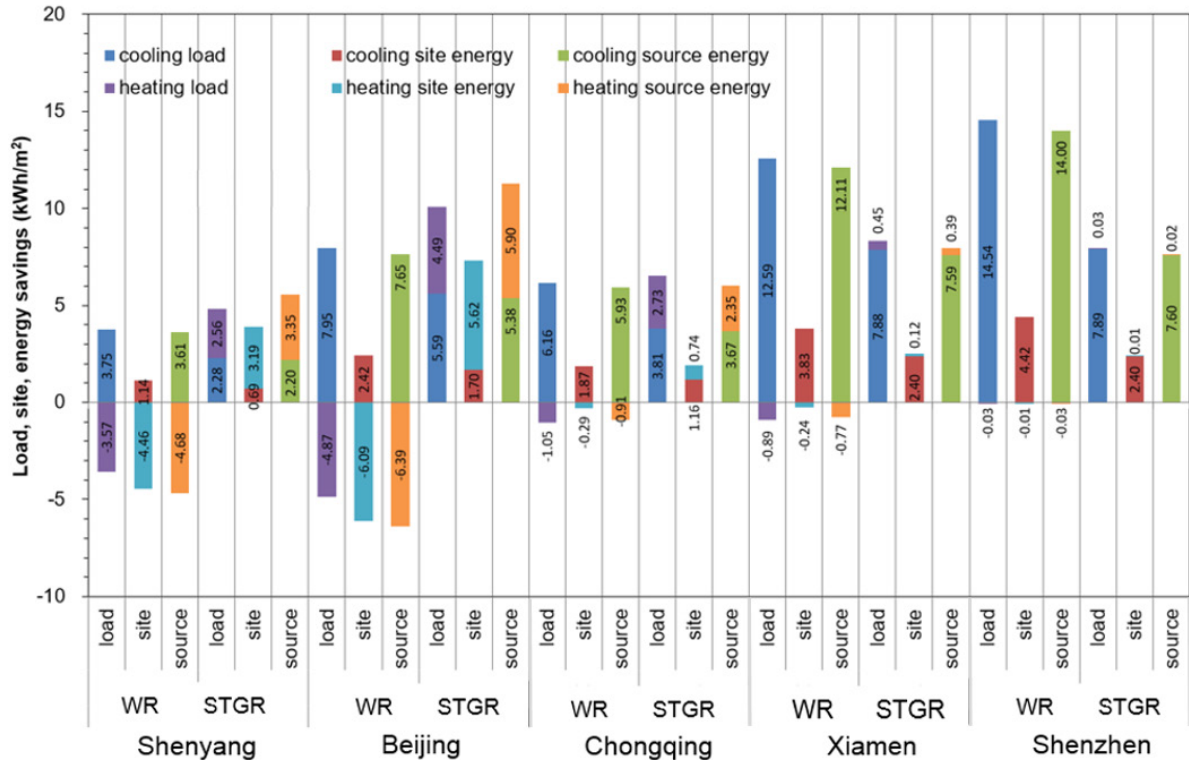
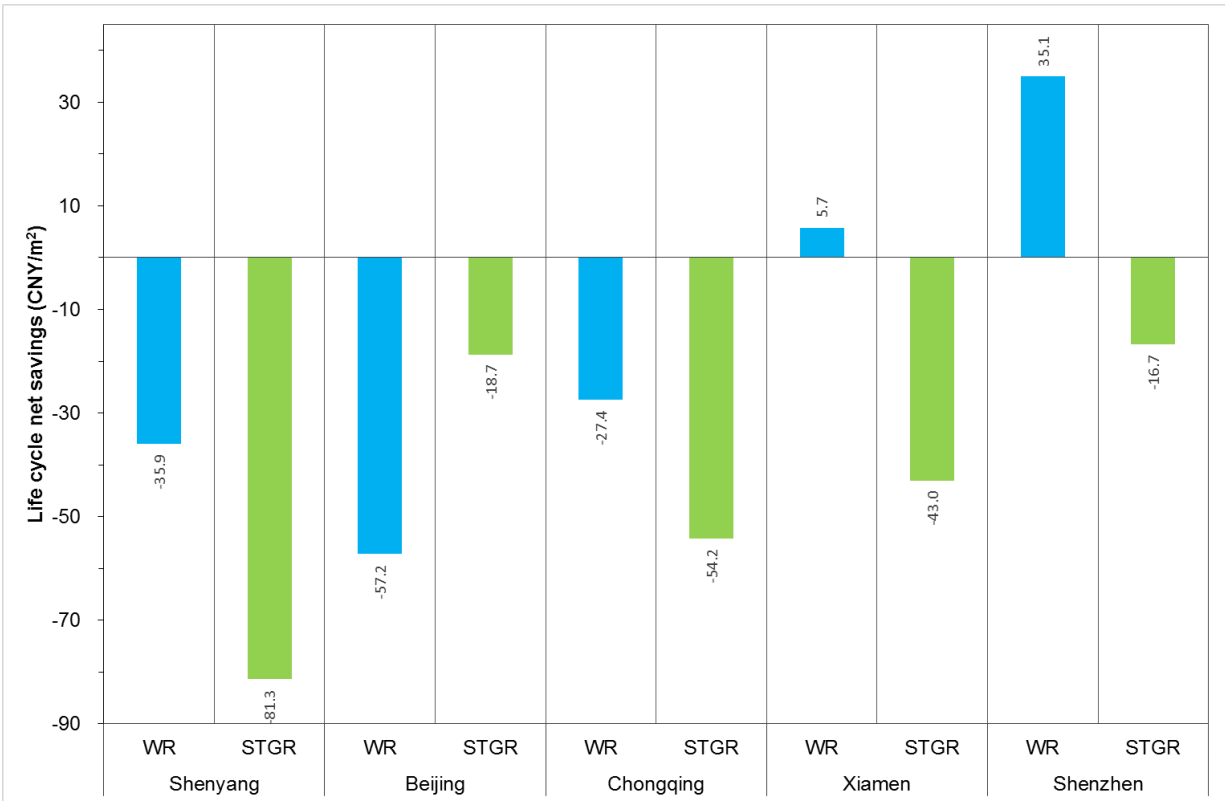


Figure 4. Annual cooling and heating load, site, and source energy savings after applying a WR or STGR retrofit to the representative office building.

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

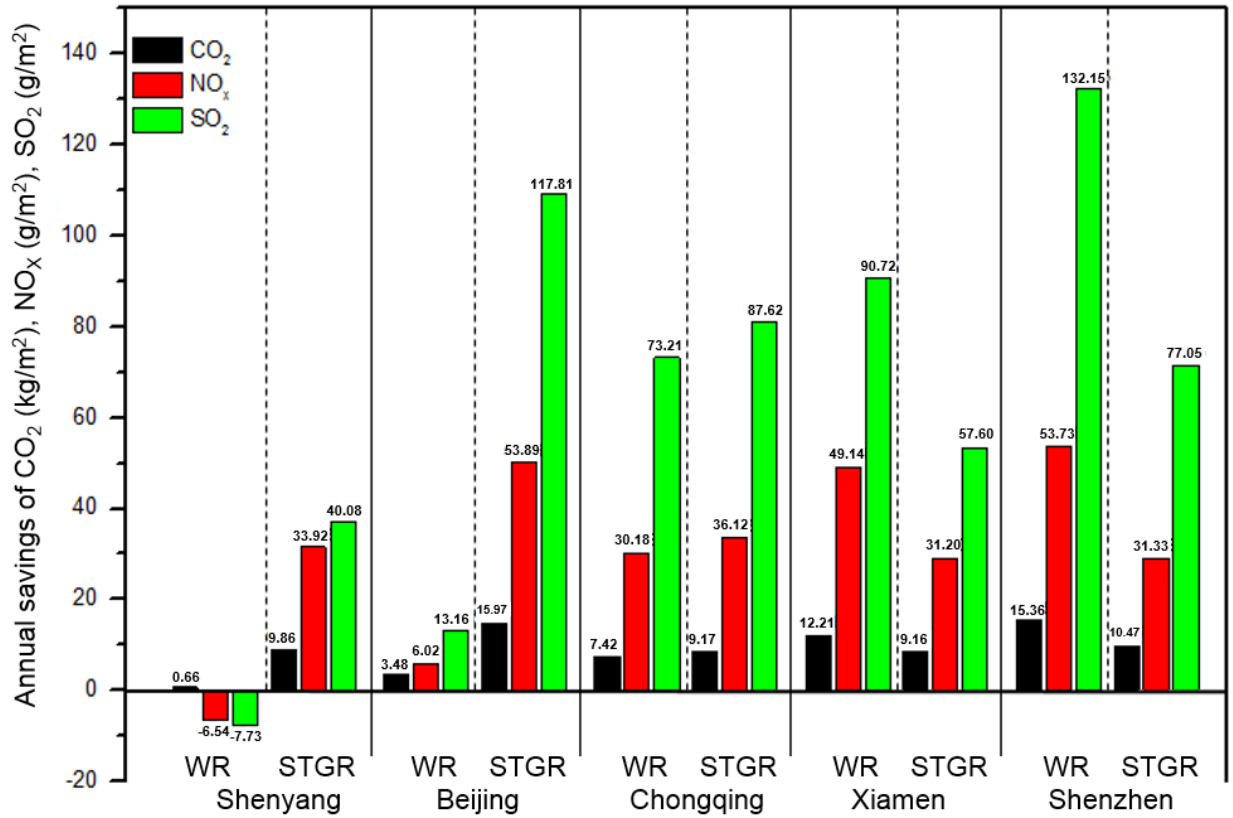


Figure 6. Annual CO₂, NO_x, and SO₂ emission savings per unit conditioned roof area after applying a white roof or garden roof retrofit to the office building prototype.

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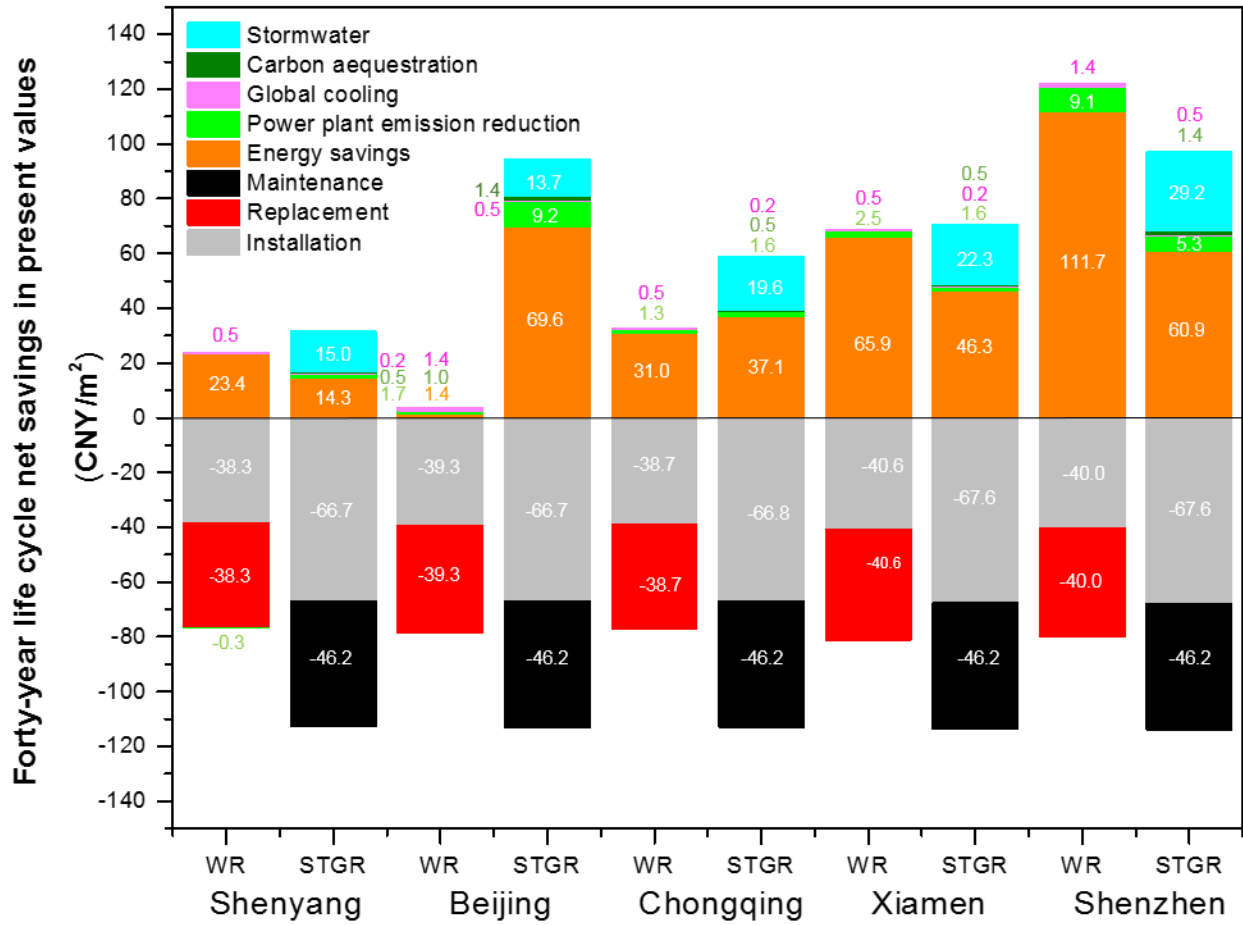


Figure 7. Comparison of WR and STGR retrofits during 40-year NS in present values for the representative office building in five cities from different Chinese climate zones.

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719 **Table captions**

- 720 Table 1 Characteristics of the representative office building simulated.
- 721 Table 2 Maximum and set values for the thermal transmittance (W/m^2K) of building envelope
722 components permitted in various Chinese cities.
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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].

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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

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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

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⁵ C15 means strength grade of concrete

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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

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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	-

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^a As of December 2018 [46]

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^b As of August 2016 [47][48][49]

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^c As of August 2018 [50]

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^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.

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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

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^a Baseline Emissions Factors for Regional Power Grids in China [53].

^b SO₂ and NO_x emissions factors of China's national power grids [54].

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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

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^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 CO₂ 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].

775 Table 8. CO₂ trading prices. The prices in Shenyang and Xiamen were assumed to equal that in Chongqing, which
776 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

777 ^a The carbon market in China [58]
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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

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^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.