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► **To cite this version:**

Long Pei, Patrick Schalbart, Bruno Peuportier. Life cycle assessment of a residential building in China accounting for spatial and temporal variations of electricity production. *Journal of Building Engineering*, 2022. hal-03678766

HAL Id: hal-03678766

<https://hal.science/hal-03678766v1>

Submitted on 25 May 2022

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Life cycle assessment of a residential building in China accounting for spatial and temporal variations of electricity production

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1 **Abstract**

2 Life cycle assessment (LCA) is widely used to reduce a building's environmental impacts in the
3 design phase. Buildings consume a lot of electricity, and heat pumps are often proposed as a way to
4 reduce greenhouse gases emissions. The electricity production mix is therefore an important aspect in
5 building's LCA. Many studies use a static national average mix, ignoring its variations in space and
6 time. This might be questioned in a large country undergoing energy transition such as China. A
7 comprehensive study on this topic for China is lacking, therefore this article aims at filling this gap by
8 investigating how the variations of the energy mix at spatial (five regions in five climate zones) and
9 temporal (four future energy mix scenarios) scales influence the LCA results. A model is proposed to
10 evaluate local future energy mixes. The life cycle inventory (LCI) database was contextualised
11 considering different local energy mixes. Environmental impacts calculated using the local energy
12 mixes and the national average energy mix were compared in the static approach and the dynamic
13 approach (future scenarios are considered) for a residential building. The results indicated that using a
14 national average mix instead of a local mix in the static approach brought non-negligible differences
15 for most provinces, e.g. the overestimation of global warming potential (GWP) reached 500 % in
16 Yunnan. Similarly, differences between the static and dynamic approaches are large for most
17 environmental impact indicators, e.g. the difference in GWP could reach around 900 % in Guangdong.
18 The differences highly depend on the prospective future scenarios and showed regional features. This
19 paper highlights the importance of the choice of energy mix in buildings' LCA in China regarding
20 both spatial and temporal scales, which is beneficial for more reasonable decisions.

21 **Keywords:** Life cycle assessment; electricity production mix; future scenarios; environmental
22 impacts; residential buildings

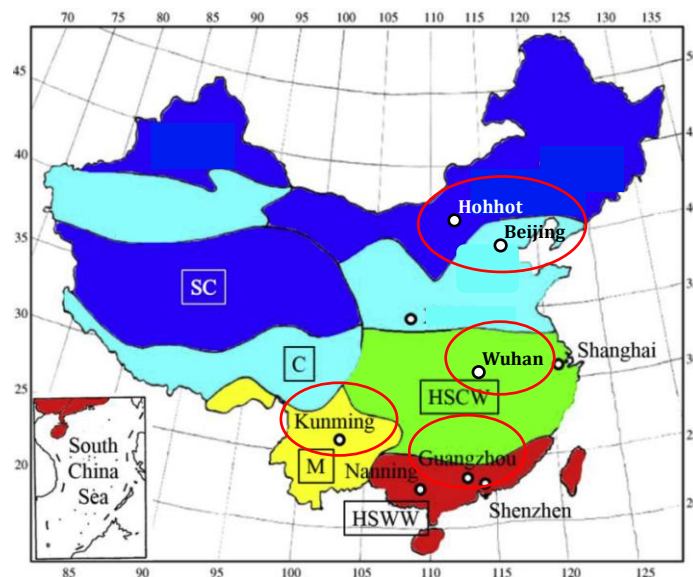
23 **1 . Introduction**

24 Buildings are recognised as major contributors to various environmental impacts in China.
25 Building energy consumption is one of the three main energy consumption domains including industry
26 and transportation, accounting for approximately 20 % of China's total primary energy in 2018 [1].
27 The building sector is one of the main sources for greenhouse gases (GHG) emissions with the
28 consequence of global warming [2]. Other impacts are also observed such as land use, water use,
29 waste generation [3], impact on human health and biodiversity [4], or even some indirect effects like
30 radiation waste production from nuclear power plants which happens due to electricity generation for
31 supplying energy for buildings, etc. China is transforming to a more sustainable and environment-
32 friendly society, and many policies have been launched to reduce the environmental impacts such as
33 energy consumption and GHG emissions [5,6], especially regarding buildings [7]. The building sector
34 is considered to be a key actor to achieve this target. The evaluation and mitigation of the
35 environmental impacts of buildings are significant to help the designers towards a better building
36 design for the environment.

37 Life cycle assessment (LCA) is a common tool used for the quantification of the environmental
38 performance of a building [8] and decision-making in the design process of buildings [9]. Being an
39 essential background system in LCA, the energy mix (or electricity production mix) strongly
40 influences the LCA results in some context [10], especially for buildings [11,12]. Different energy
41 mixes cause different impacts of building materials during fabrication. Even though construction
42 materials gain importance in contribution analyses due to the development of low-energy buildings,
43 the energy consumption during the operation stage remains a major contributor [13]. Current practice
44 in LCA is to use an annual average electricity supply mix based on a documented reference year [14].

45 However, this method may not be appropriate in some cases in China, for mainly two reasons
46 regarding spatial and temporal scales.

47 At spatial scale, China is a large country divided into five climate zones [15]: severe cold (SC),
48 cold (C), hot summer and cold winter (HSCW), mild (M), and hot summer and warm winter (HSWW),
49 as shown in Figure 1. A representative city has been selected for each climate zone, and circled in red
50 on the map. The energy performance of a building highly depends on the climate, leading to a large
51 difference of energy consumption (especially heating and cooling) between different climate zones.
52 Moreover, the electricity production mix varies with the climate zone because of the natural energy
53 resource distribution and other factors such as energy policies and strategies. Related environmental
54 impacts therefore depend on the location. It affects the materials fabrication processes involving
55 electricity (some materials such as concrete and steel are produced locally) and the electricity
56 consumed during a building's lifespan. Considering the regional characteristics of electricity, it is not
57 appropriate to directly use China's average electricity production mix. A more regional electricity
58 production mix should be taken into account in the LCA of a building.



59

60 **Figure 1: Five climate zones and representative cities in China [16]**

61 At temporal scale, to achieve the goals of low carbon society and energy transition, the energy
62 mix in the future in China will evolve by increasing the share of renewable energy and reducing the
63 share of fossil fuel [5]. Buildings are expected to have a lifespan of 15 – 50 years for commercial
64 buildings, and of 50 – 100 years for residential buildings [17]. European standards in civil engineering
65 impose a longer lifespan of around 250 years for concrete building structures [18]. The environmental
66 impacts related to electricity will vary during this lifespan. If a static energy mix is used, the effects of
67 this variation will be ignored. This is a key factor affecting the accuracy of evaluation during the long
68 lifespan of buildings.

69 The importance of the energy mix in building LCA has been emphasised in many studies. Roux et
70 al. [19] demonstrated that the use of an annual average mix instead of hourly mix data can lead to
71 underestimation of potential impacts up to 39 % for abiotic depletion potential and 36 % for GWP for
72 an energy-efficient house in France. Collinge et al. [20] assessed the differences between regional
73 average and marginal electricity generation mixes as well as the variability between predicted and
74 observed energy consumption of a conventional green building and a net-zero energy building. Ramon

75 and Allacker [21] considered three Belgian dynamic energy mix scenarios in the life cycle
76 environmental impact evaluation of buildings. They revealed the differences in the building life cycle
77 environmental impact of -29 % and +34 % compared to the current approach using the static energy
78 mix, while differences in the life cycle carbon footprint range from -59 % to +33 %. Buyle et al. [22]
79 indicated that the environmental impacts of electricity are scenario dependent, especially on the case
80 of future predictions. Kiss et al. [23] claimed that dynamic modelling of electricity taking into account
81 variation due to cross-border trading and renewable penetration will influence the LCA results for
82 buildings. Karl et al. [24] showed that the data resolution (month/day/hour) for electricity production
83 is important, and the environmental building performance may be overestimated by up to a factor of
84 two when compared with conventional grid inventory data with yearly (i.e. low) data resolutions. Ding
85 et al. [25] presented GWP of the electricity production in 2013 in 31 provinces in China, and the
86 differences in GWP were significant among the regions (e.g. 1.3 kg CO_{2eq}/kWh in Inner Mongolia and
87 0.25 kg CO_{2eq}/kWh in Qinghai). More studies [26,27] confirmed that changes in the electricity mix
88 affect buildings' environmental impacts. Therefore the dynamic energy mix has been used in an
89 increasing number of recent studies instead of the static energy mix [28,29].

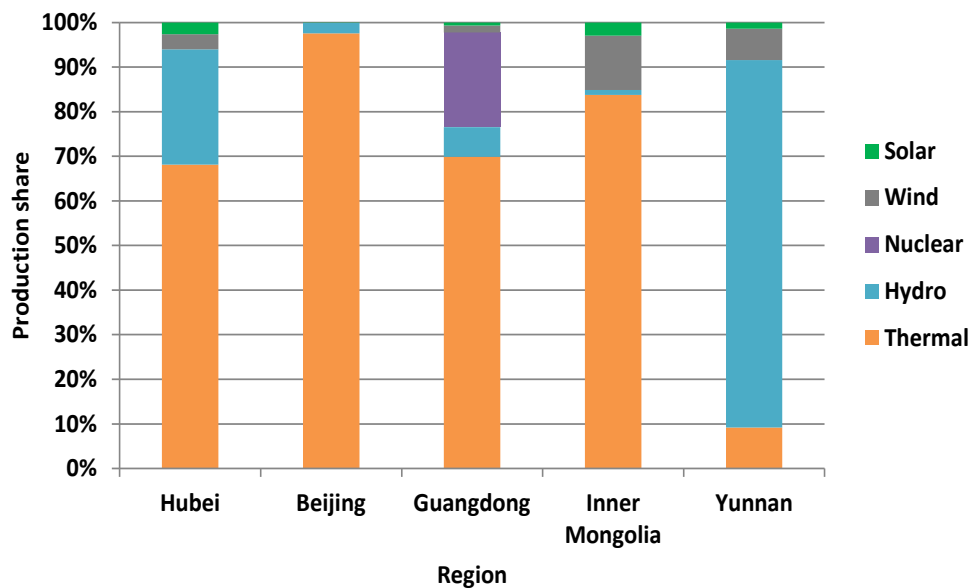
90 However, regarding the building LCA studies in China, the national static average mix is the most
91 often adopted [30,31]. This cannot reflect the regional energy mixes' characteristics and their future
92 evolutions. Few studies considered the influence of spatial or temporal variation in the electricity
93 production mix in buildings' LCA. Ma et al. [32] considered two perspective energy mix scenarios
94 and the efficiency evolution of the electricity generation in LCA for an office building in Tianjin
95 (China). Similar scenarios are used in for a green scientific research building in Beijing (China) [33].
96 Wang et al. [34] assessed the environmental impacts of heating and cooling for an office building with
97 a static energy mix from the North China Power Grid. Su et al. [35] used a regional static energy mix
98 in LCA for the operation stage of a passive building in HSCW zone in China. Su et al. [36] applied
99 dynamic LCA to a residential building located in Jiangsu Province (China) by considering the long-
100 term electricity production mix forecast according to three scenarios. But a national average electricity
101 production mix was used instead of a local one, and this assumption also appears in their new study
102 [37]. It can be inferred from the literature review that although some efforts have been made on the
103 dynamic energy mix in the future in building LCA, there is still a lack of a more comprehensive study
104 on both the spatial and temporal variations of the energy mix in China.

105 This paper is dedicated to investigate more deeply on this topic. The first objective is to generate
106 life cycle inventory (LCI) databases in the Chinese context and even the regional (provincial scale)
107 context, which can be used for other LCA studies for Chinese buildings. The second objective is to
108 evaluate the effects of the spatial and temporal variations of the electricity production mix on the
109 environmental impacts of a Chinese residential building, by applying the LCA method. Section 2
110 presents the future energy mix scenarios for China and local regions. Section 3 introduces the method
111 used in this study. Section 4 shows the contextualised databases, compares the LCA results of the
112 regional and national scales in both dynamic and static ways, and discusses some existing issues.
113 Finally, conclusions and future research needs are presented in Section 5. The major novelty of this
114 work is to show that considering a regional production mix and evolution scenarios for future years
115 leads to a high difference compared to the national present mix. This analysis is useful for LCA
116 practitioners, who are advised to pay attention to the use of an appropriate electricity production mix,
117 particularly if their study compared different heating solutions (e.g. gas versus electric or heat pump
118 heating). It should be noted that in this study, present electricity production processes were considered
119 according to a precautionary principle. This may lead to overestimate the environmental impacts but
120 on the other hand it rewards energy saving measures to a greater extent. Considering innovative and
121 low impact processes is a perspective.

122 **2 . Energy mix scenarios**

123 **2.1 Spatial scale**

124 An unbalanced distribution of natural resources e.g. wind energy, hydropower and fossil fuels
125 exists in China, resulting in an electricity production mix variation according to the location. In 2019,
126 as shown in Figure 2, wind power is more abundant in Inner Mongolia (NM), leading to a share of
127 around 12 %. Hydro power can provide more than 80 % of the total energy in a province along
128 Yangtze river such as Yunnan (YN). Larger share of nuclear energy is observed in the coastal
129 provinces such as Guangdong (GD), where it can reach 20 %. In Beijing (BJ), nearly all the electricity
130 is generated by thermal power plants. The energy mix of Hubei (HU) consists of mainly thermal
131 power (68 %) and hydro power (26 %, excluding the part transferred out of Hubei), small wind
132 power/solar power and no nuclear power.



133

134 **Figure 2: Electricity production mixes of five provinces in 2019**

135 Accounting for the climate zone and the renewable energy features, the capital city of one
136 representative province was chosen for each climate zone in this study (therefore, they do not cover
137 the whole electricity production in China but are rather representative of climate conditions). The
138 locations of the cities are shown in Figure 1. Their energy mixes and energy features are shown in
139 Table 1 (data source: China Electricity Industry Annual Development Report 2019 [38], local
140 government report [39], National Bureau of Statistics of China [40], Guangdong power exchange
141 centre [41] and local electric power association [42,43]). These five regions have different energy mix
142 features due to their locations, making them appropriate to present the effects of energy mix at spatial
143 scale. The national average energy mix is mainly dominated by thermal power and hydro power.
144 Import and export of electricity from and to outside China are negligible (less than 1%) [44].

145 **Table 1: Five representative cities in different climate zones with their energy mix features**

City, province	Climate zone	Energy mix in 2019	Energy mix features
Hohhot, Inner Mongolia (NM)	Severe cold (SC)	Thermal 84 %, wind 12 %, solar 3 %, hydro 1 %	Dominated by thermal power; High wind power
Beijing, Beijing (BJ)	Cold (C)	Thermal 98 %, hydro 2 %	Dominated by thermal power; Low renewable power
Wuhan, Hubei (HU)	Hot summer and cold winter (HSCW)	Thermal 68 %, hydro 26 %, wind 3 %, solar 3 %	Dominated by thermal power; High hydro power
Guangzhou, Guangdong (GD)	Hot summer and warm winter (HSWW)	Thermal 70 %, nuclear 21 %, hydro 7 %, wind 2 %, solar 1 %	Dominated by thermal power; High nuclear power
Kunming, Yunnan (YN)	Mild (M)	Hydro 82 %, thermal 9 %, wind 7 %, solar 2 %	Dominated by hydro power; Low thermal power
National average	-	Thermal 69%, nuclear 5 %, hydro 18 %, wind 5 %, solar 3 %	Dominated by thermal power; High hydro power

146

147 **2.2 Temporal scale**

148 In this study, short term effects regarding the variation of the electricity production mix and
 149 related impacts according to the season, the day of the week or the hour of the day are not considered.
 150 Only long term (over 50 years) temporal variation is addressed.

151 **2.2.1 Future national scenarios**

152 The Energy Research Institute (ERI) of the National Development and the Reform Commission of
 153 China (NDRCC) , focusing on the carbon reduction policies to forecast the long-term energy mix in
 154 China by 2050 [45], reported three scenarios in 2009: the energy-saving (ES) scenario, the low-carbon
 155 (LC) scenario, and the enhanced low-carbon (ELC) scenario. In these three scenarios, coal was
 156 predicted to contribute 41 %, 36 %, and 29 % of the total energy in 2050, respectively, and the
 157 increase of nuclear is noticeable. The ERI released the high renewable energy penetration (HRE)
 158 scenario in 2015 [46], aiming at predicting the future energy mix in a scenario of a high renewable
 159 energy share. In this scenario, renewable energy and non-fossil fuels energy will account for 85.8 %
 160 and 91 % of total power generation respectively in 2050. These four scenarios are described in Table 2.
 161 The predicted share of each technology (technology refers to the electricity production method that
 162 constitutes the energy mix, e.g. thermal power, wind...) is shown in Figure 3 and the detailed data are
 163 listed in the supplementary material (Table S1 and Figure S1).

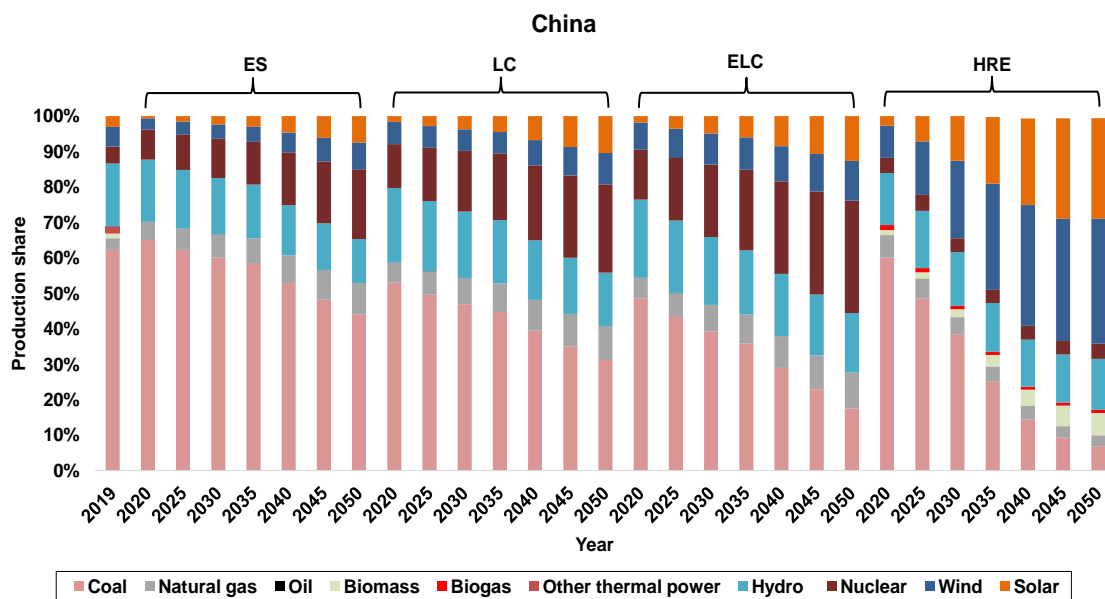
164 It should be noted that instead of every five years from 2020 to 2050 in the HRE scenario, the
 165 ES/LC/ELC scenarios only provide data for 2020, 2035 and 2050. The other years were obtained by
 166 linear interpolation. It would be useful to improve the study when prospective scenarios are detailed
 167 by including data on a yearly basis from 2020 to 2050. The corresponding abbreviation of the energy
 168 mix at a certain year for a certain scenario is ES/LC/ELC/HRE-year. To simplify the study, some
 169 technologies described in the HRE scenario are classified into a more general technology: ocean
 170 energy and geothermal energy are categorised with *other thermal power* (e.g. blast furnace gas

171 treatment); biomass pellets power, straw and stalks power, and municipal solid waste power are
 172 categorised as *biomass power*. This will not have a large influence because their shares are very small
 173 (less than 3%).

174 **Table 2: Four scenarios for the future energy mixes in this study**

Scenario	Description	Label in this paper
Energy-saving scenario (ES)	Future under the energy saving policies in 2009, without other particular policies on climate change, no significant technological breakthroughs in energy conservation and emission reduction	ES
Low-carbon scenario (LC)	Extra policies regarding carbon emissions reduction, energy structure optimisation and reduction of energy consumption	LC
Enhanced low-carbon scenario (ELC)	More efforts are made on the energy consumption reduction and clean energy technologies with the increase of Chinese economy, reduced cost and development of technologies	ELC
High renewable energy penetration scenario (HRE)	High renewable energy penetration will be reached in this scenario	HRE

175



176

177 **Figure 3: Future energy mix for China in the four prospective scenarios (ES: energy-saving**
 178 **scenario, LC: low-carbon scenario, ELC: enhanced low-carbon scenario, HRE: high renewable**
 179 **energy penetration scenario)**

180 **2.2.2 Future regional scenarios**

181 These four abovementioned scenarios describe the future energy mix at the national level.
 182 Because we could not find prospective scenarios at the level of each province but only at a national
 183 level, we considered in this study that the share of renewable production of the province to the whole
 184 country, which is highly dependent on the climatic context of the provinces, does not vary. It would be

185 useful to improve this study when prospective scenarios are available at the level of provinces. This
 186 paper proposes a model to obtain the local energy mix, based on the energy mix of 2019 and the
 187 prospective national scenarios. This model assumes that the regional nuclear or renewable energy
 188 features (the share of the local nuclear or renewable energy electricity production to that of the nation
 189 in 2019) is constant in the future. This assumption respects the abovementioned fact that if one region
 190 contributes more renewable energy production compared to other regions at present, it will also
 191 contribute more in the future, because normally this region has more energy resources of this type, e.g.
 192 [wind or solar](#). The share of nuclear is following the same trend according to the resource regarding
 193 plants cooling. The share of the total production of each province is assumed to be identical as that of
 194 2019 as well.

195 It should be noted that some provinces import electricity from other provinces in China. For
 196 example, a part of the electricity produced in Inner Mongolia is transported to the north and east of
 197 China. It is difficult to obtain the data of the interactions between provinces. In this study, the
 198 interactions are not considered; the electricity consumption mix is therefore assumed to be identical to
 199 the electricity production mix. Improvement of this approach is proposed in the perspectives.

200 For one province, in a first step, we calculate its nuclear or renewable energy features: the ratio
 201 $R_{i,2019}^k$ of its nuclear or renewable energy electricity production $E_{i,2019}^k$ to that of the nation $E_{i,2019}^{\text{nation}}$ of
 202 2019 by equation (1), as well as the its total production feature: the total electricity production ratio
 203 $R_{\text{total},2019}^k$. In a second step, as described in the assumptions abovementioned, these features are
 204 maintained identical in the future. Therefore, $R_{i,j}^k$ and $R_{\text{total},j}^k$ are constant for the future year j , as
 205 shown in equation (1):

$$\begin{cases} R_{\text{total},j}^k = R_{\text{total},2019}^k = \frac{E_{\text{total},2019}^k}{E_{\text{total},2019}^{\text{nation}}} \\ R_{i,j}^k = R_{i,2019}^k = \frac{E_{i,2019}^k}{E_{i,2019}^{\text{nation}}} \end{cases} \quad (1)$$

206 where i is the technology index for nuclear power plants or one of the renewable sources (hydro,
 207 wind, solar); j is the year (from 2020 to 2050, every 5 years); k is the province (HU, BJ, GD, NM,YN).

208 The second step is to calculate the corresponding nuclear or renewable energy, $E_{i,j}^k$, and total
 209 electricity production, $E_{\text{total},j}^k$, of each province in the future by equation (2):

$$\begin{cases} E_{\text{total},j}^k = R_{\text{total},j}^k \cdot E_{\text{total},j}^{\text{nation}} \\ E_{i,j}^k = R_{i,j}^k \cdot E_{i,j}^{\text{nation}} \end{cases} \quad (2)$$

210 where $E_{i,j}^{\text{nation}}$ is the national nuclear or renewable electricity production, and $E_{\text{total},j}^{\text{nation}}$ is the total
 211 electricity production of the nation, respectively.

212 The third step is to calculate the thermal power electricity production $E_{\text{thermal},j}^k$ by equation (3),
 213 which supplies the remaining part in the total production $E_{\text{total},j}^k$ that nuclear and renewable energies
 214 cannot fulfil:

$$E_{\text{thermal},j}^k = E_{\text{total},j}^k - E_{\text{hydro},j}^k - E_{\text{nuclear},j}^k - E_{\text{wind},j}^k - E_{\text{solar},j}^k \quad (3)$$

215 In the fourth step, if the thermal power production is negative, meaning the nuclear + renewable
 216 energy produce more electricity than the total, the negative part is distributed on nuclear and
 217 renewable resources based on their own production ratios 5 years ago (meaning the latest ratios are
 218 used) in the total non-fossil production. This step can be expressed by equation (4):

$$E_{i,j}^k = \begin{cases} E_{i,j}^k & \text{if } E_{\text{thermal},j}^k > 0 \\ E_{i,j}^k + E_{\text{thermal},j}^k \cdot \frac{E_{i,j-5}^k}{E_{\text{hydro},j-5}^k + E_{\text{nuclear},j-5}^k + E_{\text{wind},j-5}^k + E_{\text{solar},j-5}^k} & \text{if } E_{\text{thermal},j}^k \leq 0 \end{cases} \quad (4)$$

$$E_{\text{thermal},j}^k = \begin{cases} E_{\text{thermal},j}^k & \text{if } E_{\text{thermal},j}^k > 0 \\ 0 & \text{if } E_{\text{thermal},j}^k \leq 0 \end{cases} \quad (5)$$

219 The final step is to determine the electricity production of each technology in thermal power. The
 220 future ratio of each technology in thermal power at the national scale is illustrated in Table S2. These
 221 ratios are assumed to be identical at the regional scale.

222 One technology family (thermal power, nuclear and renewable) might contain several
 223 technologies, as listed in Table S3. To simplify the problem, it is assumed that the shares of
 224 technologies in each technology family are identical for all five provinces and the nation; they will not
 225 evolve with time.

226 By applying this method, the four scenarios at the regional scale are shown in Figures S2 to S6.
 227 The production of each technology for each province is illustrated in Tables S4 to S8.

228 **3. Methodology for the assessment of the environmental impacts of buildings**

229 **3.1 Case study**

230 The studied case is a high-rise residential building consisting of 34 floors with an average height
 231 of 3 m for each floor. The net floor area of the building is around 12 500 m². The heating, cooling and
 232 domestic hot water (DHW) are supplied by a ground coupled heat pump (GCHP) system.

233 **3.2 General method**

234 The method is based on LCA and dynamic building energy simulation (DBES), as shown in
 235 Figure 4. LCA is used to evaluate the environmental impacts during the case study's life span, which
 236 is divided into four stages: construction (including the fabrication of products), use (including energy
 237 and water consumption), renovation, and deconstruction (including waste treatment or possible
 238 recycling). DBES is used to predict the energy loads (e.g. heating/cooling load, DHW load and
 239 specific electricity load) in the use stage. Environmental impacts are expressed per square meter of
 240 useful area and per year, considering a building lifespan of 50 years which is the designed life
 241 expectancy proposed by the Chinese government [47]. Increasing the lifespan of buildings would
 242 decrease yearly average environmental impacts and reduce the use of materials; it will be presented in
 243 section 4.4. This method will be applied to the case study located in the five abovementioned cities.
 244 Focusing on the effects of the energy mix on the building LCA results, the architecture and the
 245 occupancy scenarios were kept identical in the energy simulation.

246 In the construction stage (at the beginning of year 2019), the data regarding the fabrication of
 247 building materials are taken from the Swiss LCI database ecoinvent v3.4 [48], and then
 248 "contextualised" considering the energy mix of year 2019 in different provinces as well as the national
 249 average energy mix in China: if the production of 1 kg of material requires electricity, the impacts of
 250 this electricity production in original regions (e.g. Switzerland) are replaced by those of the chosen
 251 mix. This contextualisation process is illustrated in detail in section 3.3.3.

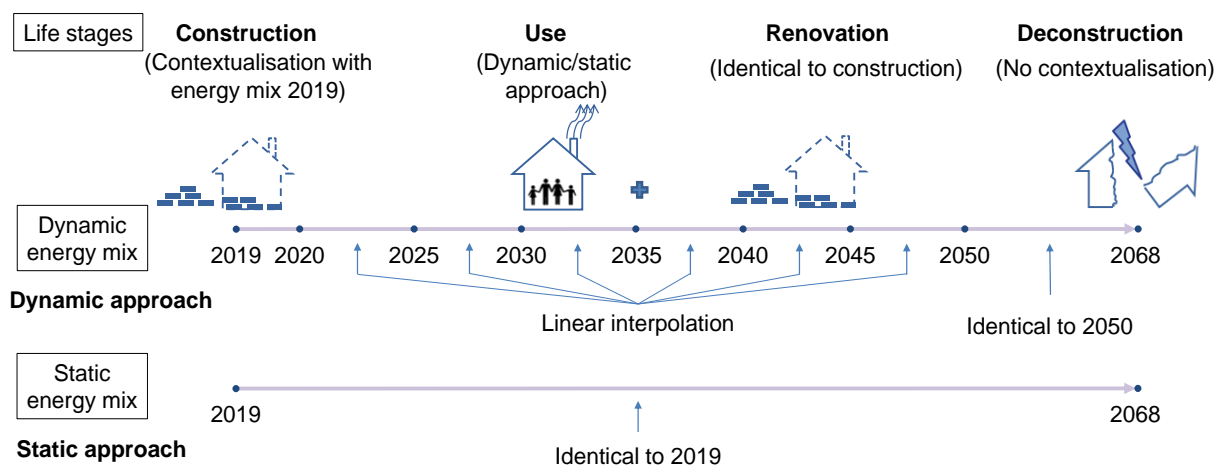
252 Regarding the use stage (year 2019-2068), the DBES tool COMFIE [49] is used to evaluate the
 253 energy loads (e.g. heating/cooling load, DHW load and specific electricity load). The weather files of
 254 the five cities are downloaded from EnergyPlus website [50]. The energy loads are then converted to
 255 electricity consumption by considering the efficiency of the equipment; the yearly electricity
 256 consumption is assumed to be identical during the lifespan, which could be refined using climatic data

257 according to climate change scenarios. The impacts of electricity are contextualised according to the
 258 national and local energy mixes, for 2019 and every five years from 2020 to 2050 corresponding to the
 259 future scenarios. The impacts of the other years are obtained by linear interpolation. Because
 260 prospective scenarios are provided up to year 2050 and no data is available after this date, the impacts
 261 of the electricity consumed in the years from 2050 to 2068 are assumed in this study to be identical to
 262 those of year 2050. It would be useful to update the study when longer term scenarios are available.

263 In the renovation stage (the replacement time depending on the lifespan of building materials and
 264 components), the replacement of materials and equipment at the end of their lives is considered. They
 265 are assumed to have the same impacts as the construction stage, meaning they are not contextualised
 266 with the future energy mix even if they are replaced in the future years. This assumption can be
 267 justified by the results shown in Figure 13 that the difference of the databases contextualised with
 268 different energy mix is not large.

269 In the deconstruction stage (at the end of year 2068), no significant electricity consumption is
 270 involved, thus no contextualisation process is considered in this stage. The building environmental
 271 impacts evaluation tool used in this study is EQUER, which has been developed since 1995 [51]. It is
 272 a tool for assessing the environmental quality of buildings based on a LCA method, in order to help
 273 stakeholders and particularly designers to better account for environmental consequences of their
 274 choices. It is linked to the DBES tool COMFIE which provides the energy consumption of the
 275 building for heating, cooling and other uses. After creating the life cycle inventory, using the LCI
 276 database ecoinvent v3.4, EQUER calculates environmental impacts (e.g. GHG emissions) over the
 277 entire lifespan (i.e. the four abovementioned stages) of the building. Its reliability was studied in
 278 several projects [52,53].

279 The effects of the energy mix on the environmental impacts can be determined by comparing two
 280 approaches in the use stage: dynamic versus static energy mix approach. The dynamic energy mix
 281 approach uses the yearly evolving impacts of electricity according to the scenarios. On the contrary,
 282 the static energy mix approach considers constant impacts for all years, corresponding to the ones at
 283 the beginning of year 2019. Taking into account four future energy scenarios (ES, LC, ELC and HRE)
 284 and five provinces (HU, BJ, GD, NM and YN), it is possible to compare to the national average
 285 energy mix to determine the spatial and long term temporal effects.



286

287

Figure 4: Illustration of the method

288 **3.3 LCA method**

289 **3.3.1 Goal and scope**

290 The main goal of LCA in this study is to determine the effects of the spatial variations (five
291 regions in five climate zones) and long term temporal variations (four future scenarios) of electricity
292 production mix on the environmental impacts of a residential building in China.

293 The evaluation scope covers the entire life cycle of the residential building, consisting of the
294 construction stage, the use stage, the renovation stage and the deconstruction stage (including possible
295 recycling). The system boundaries include the processes in the building (i.e. the energy and water
296 consumption), the upstream processes (i.e. mine exploitation, energy production, materials fabrication
297 and transportation), and the downstream processes (i.e. treatment of materials at end-of-life). Focusing
298 on the environmental impacts of the building, the daily home-work transportation and domestic waste
299 generation are not considered. The functional unit is defined as 1 m² net dwelling floor area over 50
300 years, equipped with an air conditioning system maintaining the temperature between 18°C and 26°C.

301 **3.3.2 Life cycle inventory (LCI)**

302 The quantity of each material is calculated in EQUER and the corresponding product inecoinvent
303 is contextualised and used in the evaluation. The quantities of materials and equipments used in the
304 residential building are summarised in Table S9. In the assumptions, the quantity of materials
305 transported to the construction site is 5 % higher than the needed materials in order to account for on-
306 site processes, broken elements and superfluous purchased quantities. The materials are transported by
307 diesel truck of 28 tonnes. The average distance from the material factories to the construction site is
308 assumed to be 100 km. A sensitivity study was performed and showed that this parameter has little
309 influence on the results. Therefore because the topic of the article is the influence of the electricity
310 mix, we consider that collecting more detailed data on material transport is out of the scope of this
311 study. The building elements lifespans are 10 years for finishes, 20 years for the equipment, 30 years
312 for windows and doors, and 50 years for the building itself. The materials and equipments are replaced
313 at their end of life in the renovation stage. The distance from the site to landfill plant in the
314 deconstruction stage is 20 km. All deconstruction waste is assumed to be landfilled; this has little
315 influence because end-of-life is a minor contributor to impacts of buildings compared to the use and
316 construction stages [54].

317 Regarding the energy consumption, there are four main aspects to be considered: heating, cooling,
318 DHW and specific electricity (including lighting). Heating, cooling and DHW are provided by the
319 GCHP system driven by electricity. The average seasonal coefficients of performance (COPs) for
320 heating, DHW and cooling are 3.1, 3 and 3.9 respectively [55]; they are assumed to be identical for all
321 cities. The specific electricity is supplied by the electricity grid. The water network leakage is set at
322 20 %, and the hot and cold water consumptions are set at 40 litres/day/person and
323 100 litres/day/person. The total number of occupants in the building is 498, according to the number
324 and type of the apartments.

325 **3.3.3 Life cycle impact assessment (LCIA)**

326 In EQUER, the environmental impact indicators for a building have been updated according to the
327 progress of life cycle impact assessment knowledge. In this study, twelve indicators are used to
328 comprehensively evaluate a building's environmental impacts, as shown in Table 3. They are chosen
329 in order to cover the three main areas of concern in LCA: human health, ecosystem quality and
330 resources. A limited set of five midpoints indicators covers the main contributing impact categories
331 that damage ecosystem quality and human health (climate change, photo-oxidant formation,

332 acidification, eutrophication, land use). One midpoint indicator expresses abiotic and fossil resources
333 depletion potential. Two endpoint indicators express total damage to human health in DALYs
334 (Disability Adjusted Life Years), and total damage to ecosystems in PDF.m2.year (Potentially
335 Disappeared Fraction of species over a certain territory and during a certain time). They consider
336 damages from a broader set of impact categories than those used as midpoint indicators, e.g. ozone
337 layer depletion and freshwater ecotoxicity. Those environmental indicators (in the sense of LCA) are
338 supplemented with four flows indicators (energy, water used, waste and radioactive waste). Energy
339 and water used are chosen because they are consumed throughout the lifespan of a building. Waste is a
340 meaningful concern in the building sector, particularly when dealing with circular economy.
341 Radioactive waste is significant for the nuclear production technology. More details regarding the way
342 they were chosen could be found in Appendix H in the PhD thesis of Pannier [56].

343 The LCIA methods used for calculating each indicator are also shown in Table 3. Flow indicators
344 of waste, radioactive waste and water used are calculated with EQUER based on life cycle inventory
345 analysis. Energy indicator is calculated with the method of reference Cumulative Energy Demand
346 (CED). The six midpoint indicators are based on widely used and recommended LCIA methods from,
347 e.g., Intergovernmental Panel on Climate Change (IPCC) or International Reference Life Cycle Data
348 System (ILCD). The endpoint indicators regarding biodiversity and human health are built by first
349 converting a set of midpoint indicators to a set of endpoint indicators which are then aggregated into
350 indicators of total damage to each area of concern. The contributing impact categories and the
351 midpoint-to-endpoint conversion factors are shown in Tables S10 and S11. In order to cover a broader
352 range of contributing impact categories, supplementary midpoint indicators from ILCD recommended
353 LCIA methods are used [57]. Those indicators are only involved in the endpoint calculation procedure
354 and not shown to the user to facilitate the interpretation of the LCIA results. Hence, the shown
355 midpoint and endpoint indicators should be interpreted separately. The midpoint-to-endpoint
356 conversion factors are retrieved from Impact World+ (Jolliet et al., 2016) and ReCiPe 2016 [58] in
357 consistency with the set of midpoint contributing indicators. This choice was made as none of these
358 LCIA methodologies were fully implemented in EQUER at the time of this study.

359 **Table 3: Twelve environmental impact indicators in EQUER**

n°	Indicator	Unit	Method	Legend	Source
1	Global warming potential (GWP) (100 years)	kg CO ₂ eq.	Intergovernmental Panel on Climate Change (IPCC) 2013: climate change GWP 100a	Global warming	[59]
2	Acidification potential	kg SO ₂ eq.	International Reference Life Cycle Data System (ILCD) 1.0.8 2016: freshwater and terrestrial acidification	Acidification	[57,60,61]
3	Cumulative energy demand (CED)	MJ	CED: fossils and renewables	Energy	[62]
4	Water used	L	EQUER	Water	[56] Annex H
5	Waste	kg	EQUER	Waste	[56] Annex H
6	Eutrophication potential	kg PO ₄ eq.	ILCD 1.0.8 2016: freshwater eutrophication	Eutrophication	[57,63]
7	Photochemical ozone production	kg ethylene eq.	ILCD 1.0.8 2016: photochemical ozone creation	Photochemical ozone	[57,64]
8	Radioactive waste	m ³	EQUER	Radioactive waste	[56] Annex H
9	Land use	m ² .year	Ecosystem damage potential : land occupation	Land	[65]
10	Abiotic and fossil resources depletion potential	kg antimony eq.	CML IA : elements and fossils, ultimate reserve	Resource	[66]
11	Damage to biodiversity	PDF.m ² .year	see Table S10	Biodiversity	-
12	Damage to human health	DALYs	see Table S11	Human health	-

360 ecoinvent v3.4 provides life cycle inventories (i.e. quantities of raw materials used and pollutants
 361 emitted to the air, water and ground), allowing impact indicators to be derived for material fabrication,
 362 energy processes etc. and particularly for 1 kWh of electricity produced by different technologies at
 363 high voltage level (above 24 kV) for China. It also includes inventories for grid infrastructure [67].

364 Life cycle impacts of 1 kWh delivered to the low voltage level (below 1 kV) by a given
 365 technology, I_m , include impacts related to electricity production using the technology and impacts
 366 related to the network infrastructure [19], as shown in by equation (5):

$$I_m = C_f \times (LCI_m \times (1 + l) + LCI_{\text{network},m}) \quad (5)$$

367 where m is the technology index (1 for coal, 2 for natural gas, etc.), C_f is the characterisation
 368 factor matrix, LCI_m is the life cycle inventory of one kWh produced by technology “ m ”, $LCI_{\text{network},m}$ is
 369 the life cycle inventory of the electricity network infrastructure per kWh supplied in China for
 370 technology “ m ”, and l is the level of losses. l represents electricity lost during transmission in the
 371 transport network (national and interconnection high voltage network), conversion and transmission in
 372 the distribution network (national low and medium voltage network, below 24 kV). 2 % losses are
 373 accounted for the transport network and 4 % losses for the distribution network [38].

374 Because the main aim of this study is to investigate the impacts of different energy mixes, it
 375 should be noted that each technology that constitutes the energy mix is assumed independent of time
 376 and region, thus the impacts of each technology is constant through a building’s lifespan for all
 377 regions in China. For example, all coal plants are assumed to be equivalent no matter which region
 378 they are in, in which year they were constructed, or which efficiency and pollution control
 379 technologies they are equipped with. The ecoinvent v3.4 database was used regarding environmental
 380 data for the technologies considering a location in Hubei, China, except for nuclear and biomass,
 381 because the corresponding technologies in Hubei are not available in ecoinvent v3.4. Thus, the
 382 inventory and impacts of these two technologies are based on Guangdong’s location in ecoinvent in
 383 this study.

384 All technologies are considered to produce electricity at high voltage (above 24 kV), except for
 385 photovoltaic systems (considered to release electricity at low voltage). By accounting for the share of
 386 each technology, environmental impacts ($I_{\text{loc},\text{year}}$) of 1 kWh supplied by the grid in a certain location
 387 (nation or province) and in a certain year is the sum of environmental impacts of each technology
 388 weighted by its contribution in the mix, as indicated in equation (6):

$$I_{\text{loc},\text{year}} = \sum_{m=1}^n R_{\text{loc},\text{year}}^m \times I_m \quad (6)$$

389 where n is the number of technologies (10 in total, as listed in Table S3), $R_{\text{loc},\text{year}}^m$ is the share of
 390 technology m in a certain location and in a certain year, and I_m is the impacts of 1 kWh produced by
 391 technology m .

392 The contextualisation process of a material is accomplished by replacing the electricity used in the
 393 material fabrication (e.g. the electricity in France) with local electricity in China which can be in a
 394 province or national context. The other inventories except electricity related to this material are
 395 assumed to be the same, meaning that their impacts are considered identical in all Chinese contexts.
 396 For example, the impacts of one material in a certain location in China and in a certain year, $I_{\text{loc},\text{year}}^{\text{material}}$,
 397 can be contextualised based on the French database by equation (7):

$$I_{\text{loc},\text{year}}^{\text{material}} = I_{\text{FR}}^{\text{material}} - E \times I_{\text{FR}} + E \times I_{\text{loc},\text{year}} \quad (7)$$

398 where $I_{\text{FR}}^{\text{material}}$ is the impacts of this material in the French context, E is amount of electricity
 399 used in the material fabrication and I_{FR} is the impacts of one kWh electricity in France.

400 3.3.4 Interpretation

401 The interpretation phase mainly focuses on how the energy mix influences the LCI databases and
 402 LCA impacts of a building in China. The importance of appropriately choosing the energy mix is also
 403 revealed. This will be discussed in the next section.

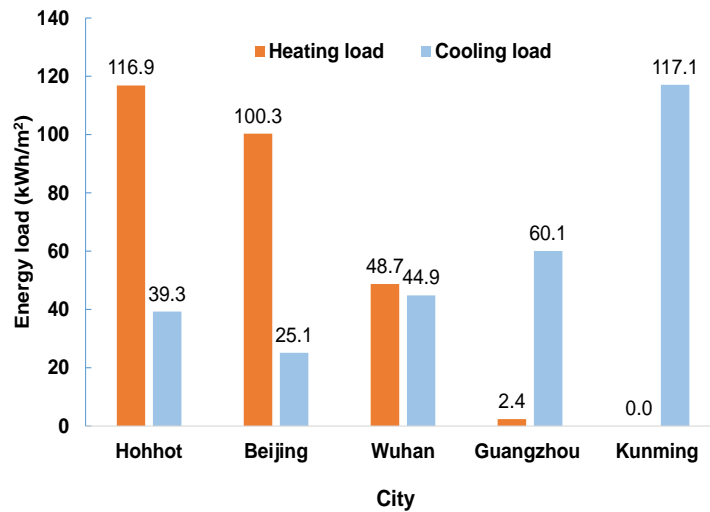
404 **4 . Results and discussion**

405 **4.1 Energy simulation results**

406 According to the Chinese building energy standard [68], the heating and cooling thermostat
407 setpoints are 18 °C and 26 °C for the whole year. The natural ventilation is 1 ach (air change per hour)
408 and an additional 0.2 ach accounts for the infiltration ventilation. The internal heat gain is 4.3 W/m²
409 for all the time. The occupancy is 0.02 person/m² from 8h00 to 17h00 from Monday to Friday and the
410 rest of the time, it is 0.04 person/m². The metabolic internal gain is 80 W/person.

411 The heating and cooling loads of the studied case located in different cities are shown in Figure 5.
412 The heating load of Hohhot located in SC zone is the largest, reaching 116.9 kWh/m². The heating
413 load of Guangzhou located in HSWW zone is small (2.4 kWh/m²). The yearly final energy
414 consumption per m² floor area is shown in Figure 6. The specific electricity consumption and the
415 electricity consumption for DHW are estimated to be 37.6 kWh/m² and 6.9 kWh/m² per year
416 respectively and they are assumed to be identical for all the five cities. The yearly total final energy
417 consumption of Guangzhou is the smallest (60.6 kWh/m²) and Hohhot has the largest total
418 consumption of 92.2 kWh/m².

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Figure 5: Energy performance of the studied case for the five cities

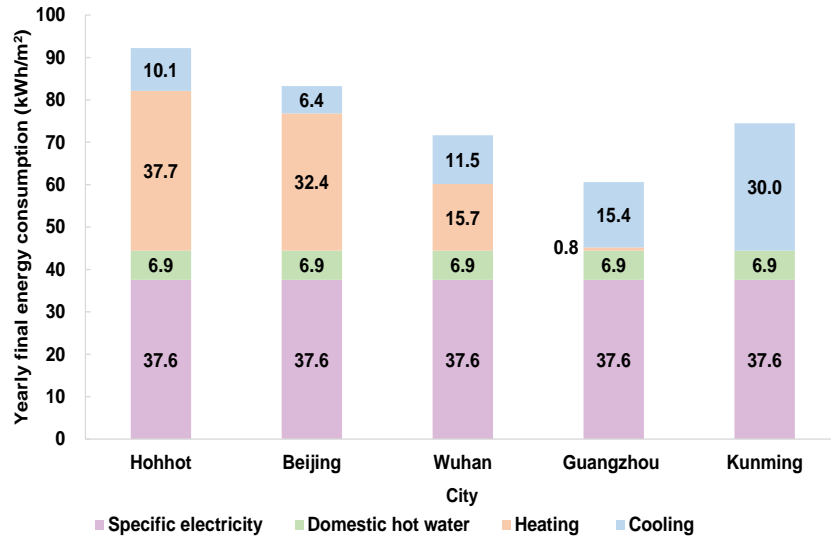


Figure 6: Total yearly final energy consumption per m² floor area for five cities

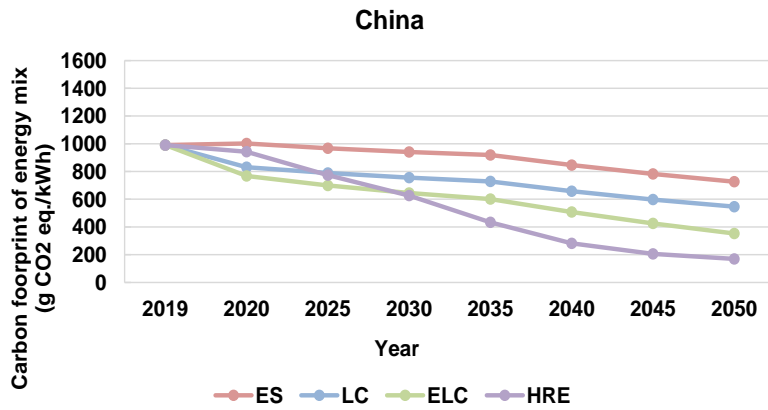
4.2 Contextualised database comparison

4.2.1 Carbon footprint of energy mixes

The environmental impacts of one kWh of electricity were obtained after national and local contextualisation, as listed in Tables S12 to S17. The carbon footprints of the energy mix at the national and provincial levels are shown in Figure 7 to Figure 12 as an example, which is often the focus of environmental policies (however, other impacts are also important in the ecodesign of buildings). On average, 1 kWh electricity of the national average energy mix in 2019 emits 990 g CO_{2eq}; it emits 980 g, 1391 g, 1002 g, 1201 g and 148 g CO_{2eq} for Hubei, Beijing, Guangdong, Inner Mongolia and Yunnan respectively. The energy mix of Beijing is dominated by thermal power, resulting in the highest CO_{2eq} emissions (40 % higher than the national average mix) among all five provinces. 82 % of electricity in Yunnan in 2019 is generated by hydro power, which is a much cleaner technology compared to thermal power, leading to the lowest emissions (85 % lower than the national average mix). Compared to the results presented by Ding et al. [25], CO_{2eq} emissions of regional electricity production in this study are similar for Inner Mongolia (1300 g/kWh by Ding et al. and 1200 g/kWh in this study) and Guangdong (700 g/kWh by Ding et al. and 1000 g/kWh in this study). The differences in Hubei, Yunnan and Beijing are larger, because of different mix in Hubei (38.4 % thermal and 61.6 % hydro in 2013 by Ding et al., but 68.2 % thermal and 25.8 % hydro in 2019 in this study) and Yunnan (27.5 % thermal and 70.9 % hydro in 2013 by Ding et al., but 9.2 % thermal and 82.41 % hydro in 2019 in this study); and different CO_{2eq} emissions from thermal production in Beijing (660 g/kWh by Ding et al. and 1430 g/kWh in this study including transmission losses). However, the comparison strongly depends on the quality of data and the scope of LCA in each study.

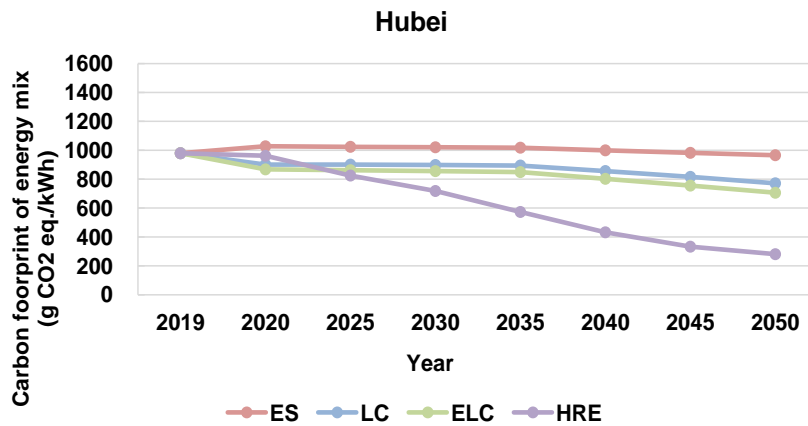
In the future scenarios, at the national scale, the HRE scenario becomes the scenario with the lowest carbon content from 2030; the CO_{2eq} emissions decrease to 169 g/kWh (83 % reduction compared to 2019). In the ES, LC and ELC scenarios, the emissions of 2050 show a reduction of 27 %, 45 % and 64 % relatively to 2019. In general, the emissions show a decreasing trend for all the provinces except Yunnan in the ES and LC scenarios. This coincides with that a part of hydro share will be replaced by thermal power in that province. For Hubei, CO_{2eq} emissions are not significantly

452 reduced in the ES scenario, but in the HRE scenario the CO_{2eq} emissions are greatly reduced to
 453 280 g/kWh in 2050, due to the increased share of renewable energy. The carbon emissions of Beijing
 454 decrease in all four scenarios, and the HRE scenario indicates a larger reduction (around 48 %) in
 455 2050 by replacing the share of coal power with biomass power compared to 2019. In Guangdong, the
 456 HRE scenario shows higher carbon emissions than other scenarios, because nuclear in the other three
 457 scenarios is significantly increased, but this might cause more other impacts (e.g. radioactive waste).
 458 Inner Mongolia is a province with high wind and solar power potential, thus in the HRE scenario, the
 459 shares of wind and solar power are high, leading a low CO_{2eq} emissions of 48 g/kWh in 2050, which is
 460 only 4 % that of 2019. It can be inferred that the carbon emissions significantly vary with the location,
 461 and this difference could be magnified with the energy mix evolution in the future.



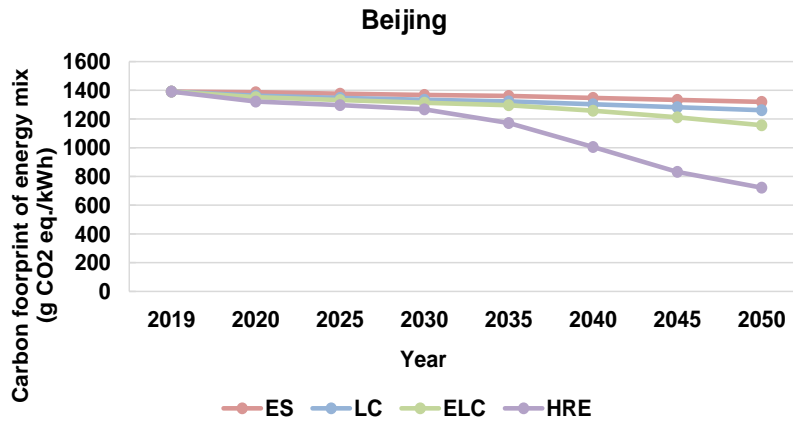
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463 *Figure 7: Carbon footprint of the national average energy mix (ES: energy-saving scenario, LC:*
 464 *low-carbon scenario, ELC: enhanced low-carbon scenario, HRE: high renewable energy*
 465 *penetration scenario)*



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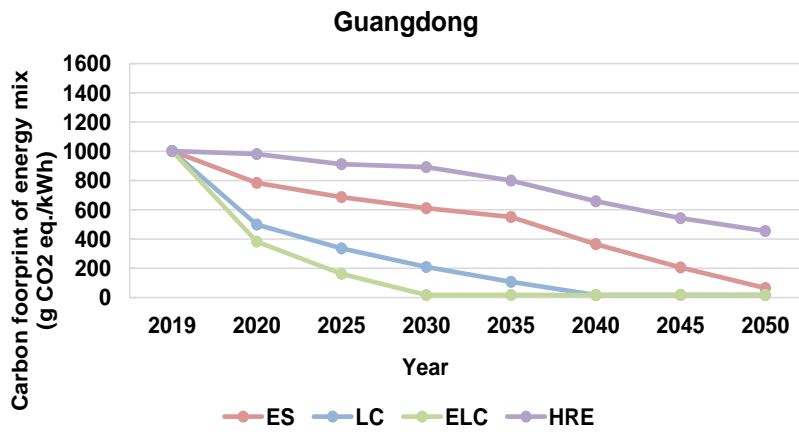
467 *Figure 8: Carbon footprint of energy mix in Hubei*



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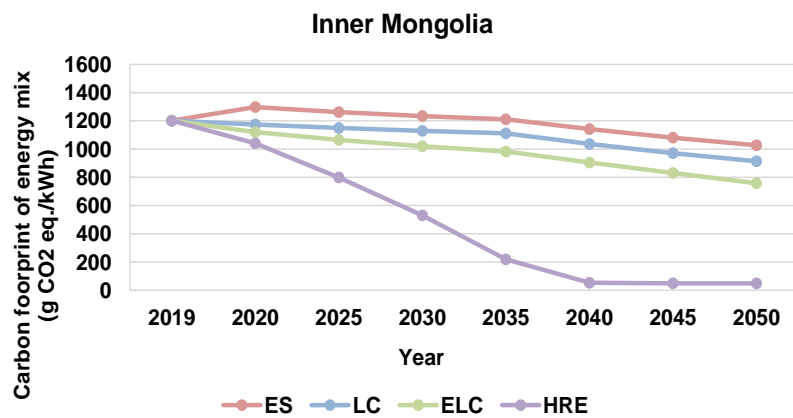
Figure 9: Carbon footprint of energy mix in Beijing



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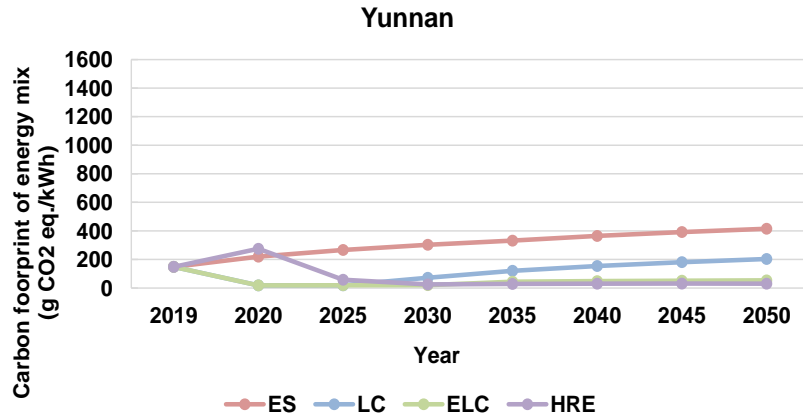
Figure 10: Carbon footprint of energy mix in Guangdong



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Figure 11: Carbon footprint of energy mix in Inner Mongolia



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Figure 12: Carbon footprint of energy mix in Yunnan

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4.2.2 Building materials

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The materials used in the studied case were contextualised using Chinese national and regional electricity mixes for the year 2019 by applying the method in section 3.3.3. The effects of choosing local energy mixes compared to the national average mix at the construction stage are shown in Figure 13. The original database is contextualised for France and it is also illustrated in the figure to present the contextualisation effects. The contextualised databases for Hubei and China are provided in Table S18 and Table S19, which can be a reference for other building LCA studies in China.

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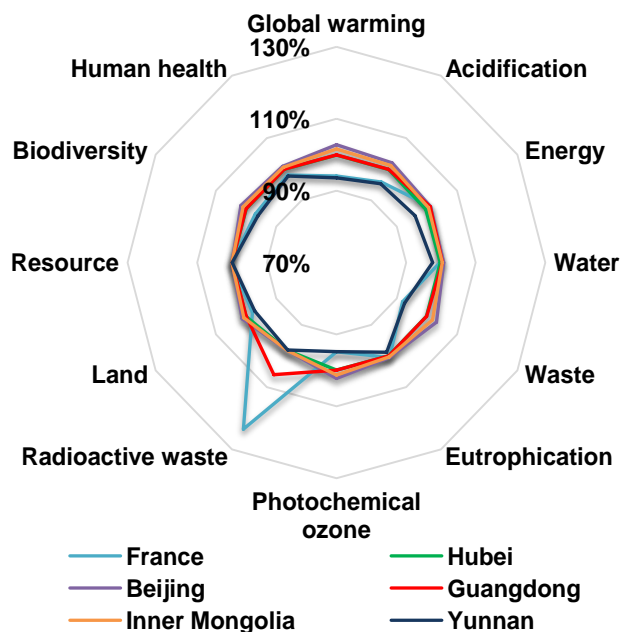
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Compared to the materials contextualised using a national average mix, the environmental impacts of the local database in China vary from -7.4 % (waste in Yunnan) to +6 % (radioactive waste in Guangdong). The impacts using the Yunnan database are the smallest and those of Beijing database are the largest (except radioactive waste). France has a nuclear dominated electricity production (over 70 %), thus the radioactive waste of the original French database is 23.5 % higher than the database contextualised with Chinese national average energy mix. However, it shows a reduction of 6 % in CO_{2eq} emissions and 4 % in acidification potential. It can be inferred that the difference between each two databases is not large at the construction stage, especially if uncertainties are considered. The effect of this difference can be even smaller if a higher life span is considered, because normally the use stage generates the most impacts. Thus the choice of a contextualised database in China is presently not a key factor affecting the total environmental impact. But it could be the case if the energy performance of buildings increases, so that material fabrication becomes an important contributor.



496

497 *Figure 13: Effects of the construction stage with local energy mix 2019 compared to national*
 498 *average mix 2019 (NATION-2019)*

499 **4.3 Impacts of energy mix evolution scenarios**

500 **4.3.1 National static versus local static**

501 This section compares the impacts of the local static (Local-S) energy mix 2019 and the national
 502 average static (Nation-S) energy mix 2019. The evolution of energy mix is not considered. No matter
 503 which energy mix is chosen, same materials are used for a certain region in the construction. Thus the
 504 construction stage is identical and contextualisation according to local context has little effect. In this
 505 study we only focus on the use stage which is the most influenced by the energy mix. The comparison
 506 results for Yunnan are shown as radar chart in Figure 14 as an example, using the local static energy
 507 mix as a reference. The results for other provinces are shown in the supplementary material
 508 (Figures S7 to S10). An evaluating system is proposed to indicate the level of difference with fonts, as
 509 listed in Table 4. The difference is divided into three levels based on the absolute difference of the
 510 results comparison. If the font colour is grey, it means the difference is minor and the substitution of
 511 energy mix is acceptable (especially if uncertainties are considered). When a bold font is used, the
 512 substitution of energy mix leads to large differences which might cause wrong decisions and this
 513 should be avoided. The font colour in black is the situation in between. The values in Table 4 are
 514 given as an example.

515 *Table 4: Evaluating system for the difference level*

Difference level	Minor	Medium	Large
Absolute difference range	≤20 %	> 20%; ≤100 %	> 100%
Indicating fond	Grey	Black	Bold

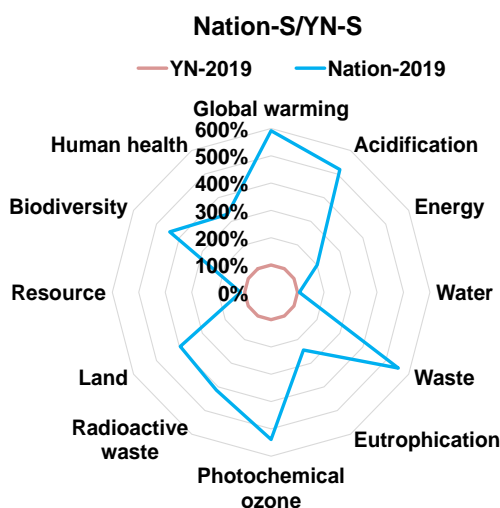
516 The impacts comparisons are summarised in Table 5. It can be inferred that for all five regions,
 517 the difference level of radioactive waste is at least medium. Guangdong is the only province where

518 radioactive waste is underestimated. This coincides with the fact that more nuclear is used in
 519 Guangdong compared to the national average. The differences for the other eleven indicators are
 520 minor in Hubei, Guangdong and Inner Mongolia, meaning it is acceptable to use a national average
 521 energy mix to evaluate these impacts. However, this simplification should be made with care in
 522 Beijing, and especially Yunnan, where ten indicators are largely overestimated due to a large share of
 523 hydro power.

524 **Table 5: Impact differences of the use stage between using a national static average mix and a local**
 525 **static mix**

	Hubei	Beijing	Guangdong	Inner Mongolia	Yunnan
Global warming	1.1%	-28.4%	-1.1%	-17.3%	491.9%
Acidification	1.1%	-27.7%	-1.0%	-17.0%	419.2%
Energy	5.4%	-14.6%	-13.5%	-6.8%	101.0%
Water	0.5%	-2.6%	-1.1%	-1.4%	6.8%
Waste	1.1%	-28.1%	-1.1%	-17.2%	454.9%
Eutrophication	1.4%	-21.1%	-0.1%	-14.0%	144.2%
Photochemical ozone	1.1%	-27.9%	-1.0%	-17.1%	439.0%
Radioactive waste	236.9%	240.1%	-69.9%	253.4%	313.6%
Land	0.6%	-25.8%	1.2%	-15.7%	296.4%
Resource	7.4%	20.6%	0.2%	-2.8%	15.3%
Biodiversity	1.1%	-26.8%	-0.9%	-16.5%	342.4%
Human health	1.4%	-24.4%	-0.8%	-15.5%	229.9%

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527

528 **Figure 14: Impacts comparison of national average mix 2019 (Nation-2019) and Yunnan mix 2019**
 529 **(YN-2019) for the use stage in Kunming, Yunnan**

530 **4.3.2 Local static versus local dynamic**

531 This section compares the differences of the impacts of the local static (Local-S) energy mix 2019
 532 and the local dynamic (Local-D) energy mix for four future scenarios in the use stage. It should be
 533 noted that taking into account the evolution of electricity production mixes, the dynamic approach is
 534 considered as the reference appropriately indicating the environmental impacts. The static approach is
 535 compared to the dynamic approach under different future scenarios to show the differences that might
 536 be caused by this simplification. These two approaches were presented in section 3.2. The difference
 537 level is still determined by the criterion in Table 4. The impacts comparisons are summarised in Table
 538 6 to Table 9. The comparison results for Yunnan are shown as radar chart in Figure 15 as an example.
 539 The results for other provinces are shown in the supplementary material (Figures S11 to S14).

540 As described in Table 2, the ES, LC and ELC scenarios share the same goal to reduce carbon
 541 emissions, with increasing policy intensity. For Hubei, Beijing and Inner Mongolia, the differences are
 542 small for all the indicators except land in the ES scenario; more indicators become yellow in the ELC
 543 scenario with stronger policies. The differences for land are always large in Hubei, Beijing,
 544 Guangdong and Inner Mongolia. In these three scenarios for Guangdong, the share of nuclear is much
 545 larger compared to the present one. As consequence, except for the small differences for CED and
 546 Water, the differences for other indicators are medium (e.g. radioactive waste) or large (e.g. GWP). In
 547 the static approach, the share of hydro power reaches 82 % in Yunnan in 2019. This leads to different
 548 features compared to other regions. In the ES scenario, all the indicators are underestimated. However
 549 in the LC scenario, the impacts evaluation is relatively accurate for 11 indicators except for land. In
 550 the ELC scenario, four indicators are largely overestimated and the differences for three indicators are
 551 medium. In the HRE scenario, Inner Mongolia is the province which is affected by using the static
 552 local mix: the differences are large for seven indicators and medium for three. This is because the
 553 electricity is mainly produced by wind and solar power in the HRE scenario instead of thermal power
 554 in 2019.

555 The results show that the static approach might cause high differences compared to the dynamic
 556 approach for most environmental impact indicators. The differences highly depend on the prospective
 557 future scenarios. The differences also show regional features. For example, in Guangdong, the
 558 difference of GWP can reach around 900 % in the ELC scenario; however it is relatively accurately
 559 evaluated in Yunnan in the LC scenario. Although the prospective scenarios might not reflect the real
 560 evolution in the future, they provide a picture of different levels of renewable energy shares. It can be
 561 inferred that the static approach which is usually adopted in the existing researches is not appropriate
 562 for building LCA considering the long lifespan of buildings. This study proposes a method with
 563 associated data for a dynamic evaluation, which can be updated as more future scenarios become
 564 available. It can be an alternative for the users for a building's LCA; furthermore a comparative
 565 analysis is possible, which could increase the reliability of the results.

566 **Table 6: Impact differences of the use stage between using a local static mix and a local dynamic**
 567 **mix in the energy-saving (ES) scenario**

<i>Energy-saving scenario (ES)</i>	Hubei	Beijing	Guangdong	Inner Mongolia	Yunnan
Global warming	-1.1%	3.5%	182.7%	6.6%	-54.8%
Acidification	0.0%	4.7%	166.5%	7.5%	-50.2%
Energy	-4.1%	-1.6%	-6.9%	0.3%	-20.2%
Water	-0.3%	0.0%	0.6%	0.3%	-1.7%
Waste	-0.7%	3.9%	174.2%	6.9%	-52.6%

Eutrophication	-0.8%	3.3%	74.2%	4.7%	-26.2%
Photochemical ozone	-1.0%	3.6%	168.5%	6.5%	-51.9%
Radioactive waste	-1.0%	1.4%	-66.8%	0.5%	-5.5%
Land	117.9%	147.5%	400.5%	140.0%	3.5%
Resource	-6.5%	0.1%	-23.6%	-6.8%	-5.3%
Biodiversity	0.8%	5.5%	148.4%	8.2%	-44.9%
Human health	-0.4%	3.9%	105.3%	6.1%	-35.9%

568 *Table 7: Impact differences of the use stage between using a local static mix and a local dynamic*
569 *mix in the low-carbon (LC) scenario*

<i>Low-carbon scenario (LC)</i>	Hubei	Beijing	Guangdong	Inner Mongolia	Yunnan
Global warming	17.0%	7.0%	567.7%	17.7%	2.5%
Acidification	25.2%	10.9%	468.7%	21.1%	5.0%
Energy	1.9%	-1.1%	-8.1%	4.8%	-1.2%
Water	0.7%	0.3%	0.9%	1.1%	0.0%
Waste	27.0%	10.8%	532.1%	21.3%	6.0%
Eutrophication	16.0%	8.5%	129.0%	13.6%	-0.4%
Photochemical ozone	22.1%	9.1%	486.5%	19.3%	3.8%
Radioactive waste	-0.3%	1.7%	-72.4%	0.0%	-2.0%
Land	153.3%	161.4%	701.3%	158.4%	38.0%
Resource	-12.6%	-0.1%	-29.1%	-15.1%	-9.4%
Biodiversity	20.6%	10.1%	359.1%	19.6%	2.8%
Human health	18.0%	8.7%	208.4%	16.3%	0.7%

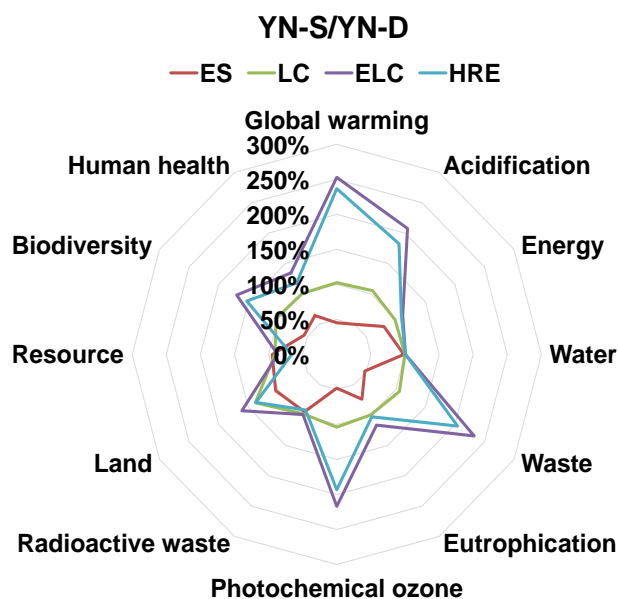
570 *Table 8: Impact differences of the use stage between using a local static mix and a local dynamic*
571 *mix in the enhanced low-carbon (ELC) scenario*

<i>Enhanced low-carbon scenario (ELC)</i>	Hubei	Beijing	Guangdong	Inner Mongolia	Yunnan
Global warming	24.7%	12.4%	913.7%	34.3%	152.7%
Acidification	32.9%	21.2%	689.8%	42.4%	107.6%
Energy	5.5%	-0.5%	-8.7%	10.7%	11.6%
Water	1.0%	0.7%	1.0%	2.2%	0.7%
Waste	35.0%	22.5%	831.2%	44.4%	132.6%
Eutrophication	19.9%	16.9%	148.1%	26.4%	16.6%
Photochemical ozone	29.8%	18.0%	730.0%	39.2%	116.9%
Radioactive waste	-0.4%	2.0%	-73.6%	-0.2%	-0.9%
Land	158.0%	184.6%	846.0%	188.1%	60.8%
Resource	-17.4%	0.0%	-30.5%	-21.6%	-13.5%
Biodiversity	27.5%	17.4%	481.7%	36.8%	69.5%
Human health	23.6%	16.3%	252.0%	31.3%	34.4%

572 **Table 9: Impact differences of the use stage between using a local static mix and a local dynamic**
 573 **mix in the high renewable energy penetration (HRE) scenario**

<i>High renewable energy penetration scenario (HRE)</i>	Hubei	Beijing	Guangdong	Inner Mongolia	Yunnan
Global warming	97.8%	42.8%	51.8%	320.3%	136.7%
Acidification	61.5%	13.4%	21.6%	252.2%	82.4%
Energy	18.3%	-6.2%	1.8%	79.3%	9.5%
Water	3.2%	3.0%	2.1%	8.1%	0.6%
Waste	103.2%	50.8%	58.9%	292.7%	104.6%
Eutrophication	39.1%	30.1%	26.8%	87.1%	2.8%
Photochemical ozone	79.1%	28.8%	37.0%	277.8%	93.2%
Radioactive waste	-10.1%	-13.3%	12.5%	-3.5%	-8.4%
Land	-71.2%	-85.3%	-82.9%	117.4%	37.0%
Resource	-42.3%	-4.9%	-15.2%	-49.9%	-33.9%
Biodiversity	50.1%	6.3%	13.9%	222.1%	52.3%
Human health	54.2%	25.9%	28.6%	146.5%	17.9%

574



575

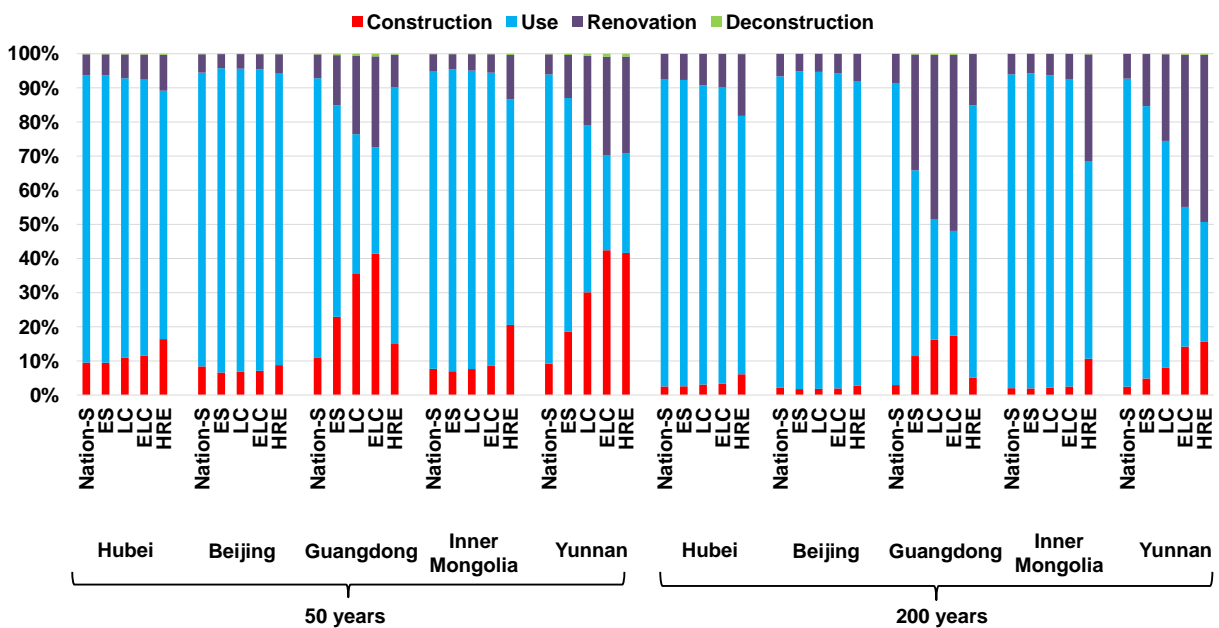
576 **Figure 15: Impacts comparison of Yunnan static mix (YN-S) and Yunnan dynamic mix (YN-D) for**
 577 **the use stage in Kunming, Yunnan**

578 **4.4 Sensitivity analysis**

579 In the previous sections, the sensitivity of LCA regarding the energy mix was illustrated. Besides
 580 that, lifespan is an important parameter that affects the total environmental impacts of a building. A
 581 sensitivity analysis was performed to investigate the effects of this parameter. The impacts of the use
 582 stage during the years after 2068 are assumed to be identical to those in 2068 because no scenario data
 583 is available beyond this date.

584 The CO_{2eq} emissions share of each stage for a lifespan of 50 years and 200 years is shown in
 585 Figure 16, evaluated by the static approach with the national average energy mix in 2019 and the
 586 dynamic approach for five regions. In general, the share of the construction stage decreases and the
 587 renovation stage contributes more when the lifespan increases. It can be inferred that the static
 588 approach with the national average energy mix in 2019 might cause non-negligible differences in the
 589 HRE scenario for these regions except for Beijing for both lifespans. It might also lead to a different
 590 order of the importance of each stage for some regions in some scenarios. For example, for a lifespan
 591 of 50 years in Guangdong, the static approach could evaluate the shares in the HRE scenario with
 592 small differences (< 7 %). However for the ELC scenario, it predicts the ranking is
 593 use > construction > renovation > deconstruction, which is contradictory to the order given by the
 594 dynamic approach: construction > use > renovation > deconstruction. This misevaluation is also
 595 observed for Yunnan in the ELC and HRE scenarios. The static approach considering a national
 596 average mix overestimates the share of the use stage, because it does not consider the CO_{2eq} emissions
 597 reduction due to more renewable energy share in the future. In common knowledge, the importance of
 598 the use stage increases with lifespan, and it contributes the most among the four stages. However, for
 599 some provinces with higher renewable/nuclear share (e.g. Yunnan in the HRE scenario and
 600 Guangdong in the ELC scenario with high nuclear production), longer lifespan leads to a larger share
 601 of the renovation stage compared to the use stage. This is because the CO_{2eq} emissions during
 602 electricity production are small, and consequently the emissions during the use stage regarding the
 603 specific electricity use are small. In this case, the choice of the contextualised material database might
 604 be more significant.

605 It can be inferred that the use of a static energy mix might lead to a wrong judgement regarding
 606 the importance of each stage, which is a potential risk for the policy decision. This is another aspect
 607 suggesting that the commonly used static approach using a national average electricity production mix
 608 is not appropriate for using buildings' LCA as a decision help. On the other hand, considering the
 609 present mix may be appropriate in a regulation according to a precautionary principle because low
 610 impact scenarios are not sure.



611

612 **Figure 16: CO_{2eq} emissions share of each stage for a lifespan of 50 years and 200 years**

613 **5 . Conclusions and future research needs**

614 This study investigates how the variations of the electricity production mix affect the LCA results
615 of a residential building in China at spatial and temporal scales. At spatial scale, five regions (Hubei,
616 Beijing, Inner Mongolia, Guangdong and Yunnan) in five climate zones were considered, and they
617 have different energy mixes due to their locations and natural resources. At temporal scale, four future
618 energy mix scenarios (ES, LC, ELC and HRE) were compared, aiming at providing a sensitivity
619 analysis regarding the future scenario.

620 This study firstly proposed a model to derive regional future energy mix scenarios from the
621 national scenario. Afterwards, the contextualisation of materials and electricity in the LCI database
622 ecoinvent v3.4 was performed under national and regional electricity production mixes. The
623 environmental impacts of a residential building were obtained by combining dynamic energy
624 simulation and LCA. The environmental impacts were compared between each local energy mix and
625 the national average energy mix, in the static approach which does not consider the future scenario and
626 the dynamic approach accounting for the future evolution.

627 The results indicated that differences were small (below 8 %) regarding the environmental
628 impacts of the material fabrication in the construction stage using the local database compared to that
629 using the database contextualised with the national average electricity mix. The use stage was the main
630 contributor in most environmental impacts and the choice of an electricity production mix highly
631 influenced the LCA results. At regional scale, using the national average mix in the static approach
632 can bring significant differences in many provinces (e.g. overestimation of GWP can reach around
633 500 % in the use stage along a 50 years lifespan in Yunnan). At temporal scale, the static approach
634 might cause high differences compared to the dynamic approach for most environmental impact
635 indicators. The differences highly depend on the prospective future scenarios and also show regional
636 features (e.g. the difference in GWP can reach around 900 % in Guangdong in the ELC scenario, but it
637 is relatively small in Yunnan in the LC scenario). A sensitivity analysis concerning the building
638 lifespan indicated that the importance of the renovation stage might be more significant than the use
639 stage when the lifespan increased in some cases.

640 One major highlight of this paper is revealing the importance of appropriate choice of energy mix
641 in building LCA in China, which is helpful for more reasonable decisions regarding mitigating
642 buildings' environmental impacts in the design phase. If the electricity exchange between regions is
643 limited, according to the grid infrastructure, the local electricity mix accounting for future evolution is
644 recommended for the future building LCA work instead of a static national average energy mix. The
645 contextualised database presented in this paper is another contribution, which can be a reference for
646 future work concerning building LCA in China.

647 More in-deep studies could be performed in the future, such as considering the power grid
648 interactions between different provinces, and a sensitivity analysis of the insulation technologies and
649 heating/cooling supply technologies for different regions. The results could be improved if technology
650 evolution in electricity generation is considered or updated future scenarios and regional prospective
651 mix scenarios are available. The environmental impacts of the electricity might vary in a short term
652 (e.g. seasonally or hourly), because different electricity production technologies are used for different
653 hours. Calibrating a model accounting for this in the Chinese context can be another perspective.

654 **Acknowledgements**

655 The authors would like to thank the financial support by China Scholarship Council (CSC) and
656 the Chair ParisTech VINCI Eco-design of buildings and infrastructure.

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List of abbreviations

ach	Air change per hour
BJ	Beijing
C	Cold climate zone
CED	Cumulative energy demand
COP	Coefficient of performance
DBES	Dynamic building energy simulation
DHW	Domestic hot water
ELC	Enhanced low-carbon scenario
ERI	Energy research institute
ES	Energy-saving scenario
GCHP	Ground coupled heat pump
GD	Guangdong
GHG	Greenhouse gases
GWP	Global warming potential
HRE	High renewable energy penetration scenario
HSCW	Hot summer and cold winter
HSWW	Hot summer and warm winter
HU	Hubei
ILCD	International Reference Life Cycle Data System
IPCC	Intergovernmental Panel on Climate Change
LC	Low-carbon scenario
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
M	Mild
NDRCC	National Development and the Reform Commission of China
NM	Inner Mongolia
SC	Severe cold climate zone
YN	Yunnan

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List of symbols

C_f	Characterisation factor matrix
E	Electricity production or electricity used during material fabrication, kWh
I	Environmental impacts
l	Electricity lost during transmission, %
LCI_i	Life cycle inventory of one kWh produced by technology “ i ”
$LCI_{network,i}$	Life cycle inventory of the electricity network infrastructure per kWh for technology “ i ”

<i>m</i>	Technology index
<i>n</i>	Number of technologies
<i>R</i>	Ratio, %

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Superscripts and subscripts

FR	France
<i>i</i>	Technology index for nuclear or renewable technology (hydro, wind, solar)
<i>j</i>	Year
<i>k</i>	Province (HU, BJ, GD, NM,YN)
loc	Location
material	Material for contextualisation
nation	National scale
total	all technologies
year	Year of the material fabrication

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