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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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Abstract

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

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

1 . Introduction

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

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

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

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

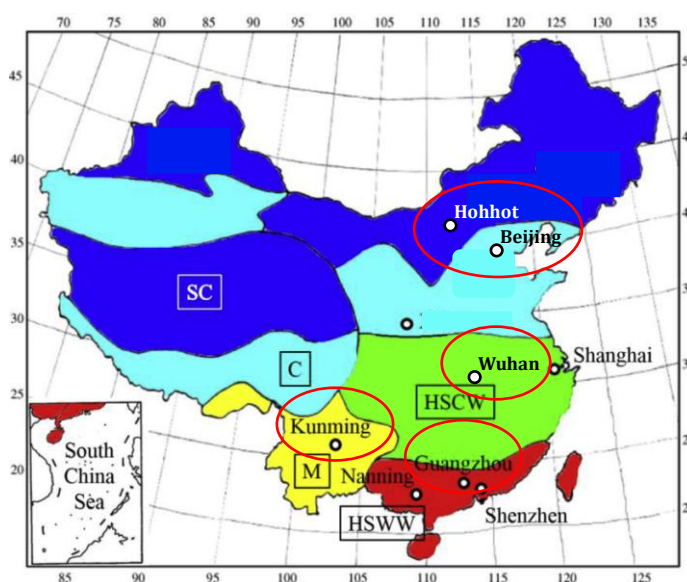


Figure 1: Five climate zones and representative cities in China [16]

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

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

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

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

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

2 . Energy mix scenarios

2.1 Spatial scale

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

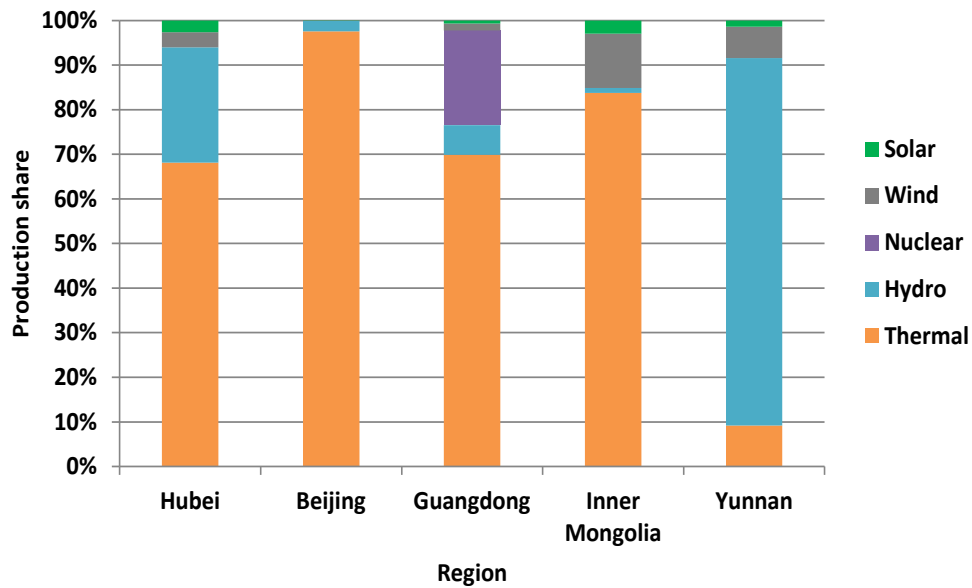


Figure 2: Electricity production mixes of five provinces in 2019

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

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

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

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

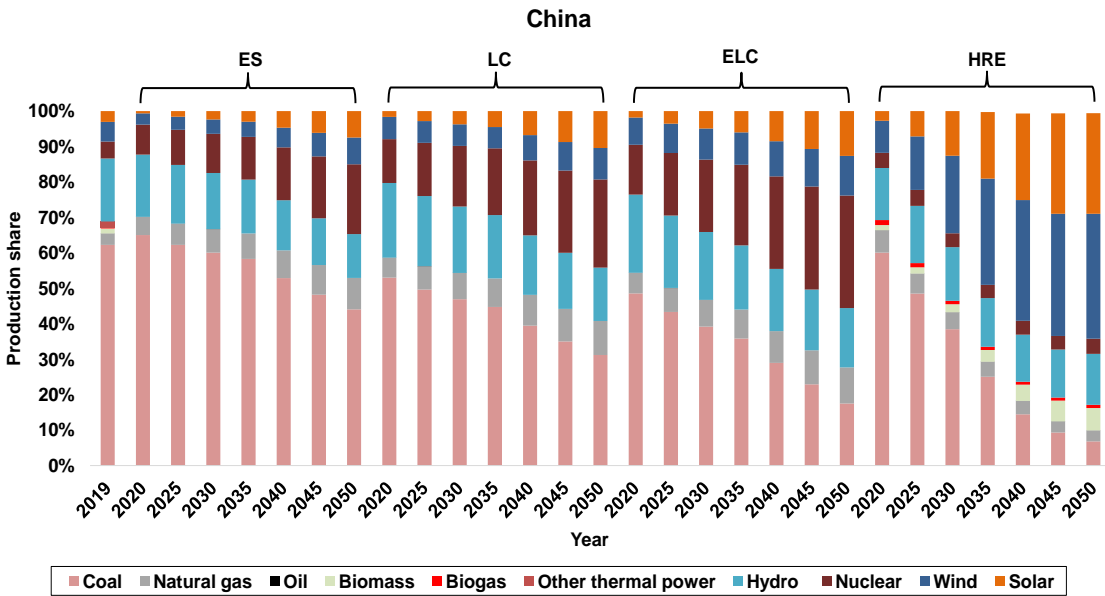


Figure 3: Future energy mix for China in the four prospective scenarios (ES: energy-saving scenario, LC: low-carbon scenario, ELC: enhanced low-carbon scenario, HRE: high renewable energy penetration scenario)

2.2.2 Future regional scenarios

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

3.1 Case study

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

3.2 General method

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

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

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

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

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

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

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

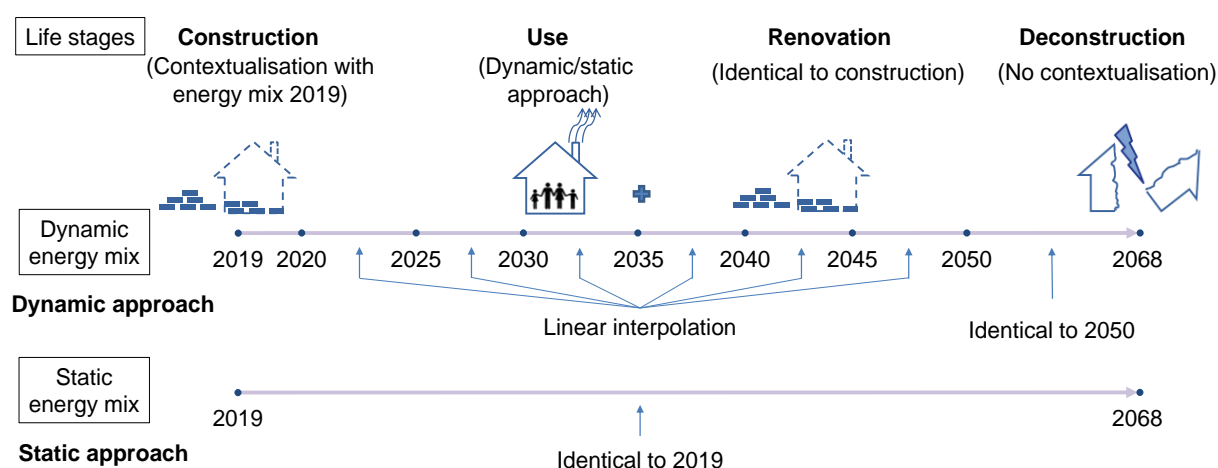


Figure 4: Illustration of the method

3.3 LCA method

3.3.1 Goal and scope

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

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

3.3.2 Life cycle inventory (LCI)

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

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

3.3.3 Life cycle impact assessment (LCIA)

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

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

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

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

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

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

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

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

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

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

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 technology m in a certain location and in a certain year, and I_m is the impacts of 1 kWh produced by technology m .

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

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

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

3.3.4 Interpretation

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

4 . Results and discussion

4.1 Energy simulation results

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

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

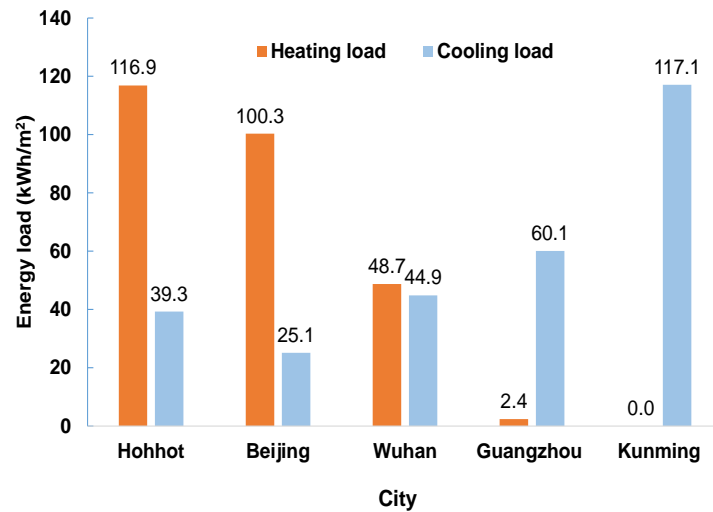


Figure 5: Energy performance of the studied case for the five cities

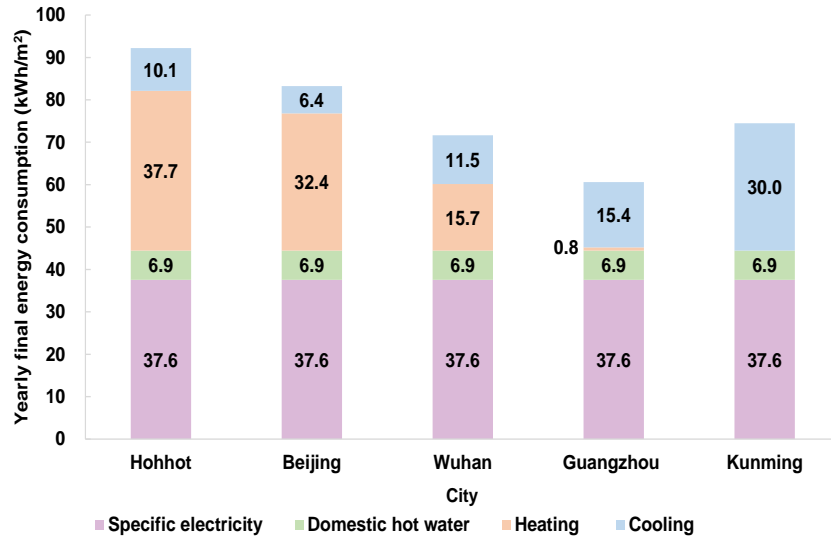


Figure 6: Total yearly final energy consumption per m² floor area for five cities

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

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

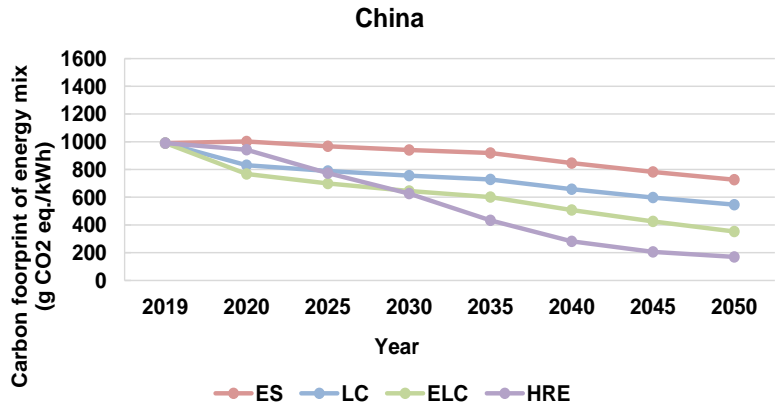


Figure 7: Carbon footprint of the national average energy mix (ES: energy-saving scenario, LC: low-carbon scenario, ELC: enhanced low-carbon scenario, HRE: high renewable energy penetration scenario)

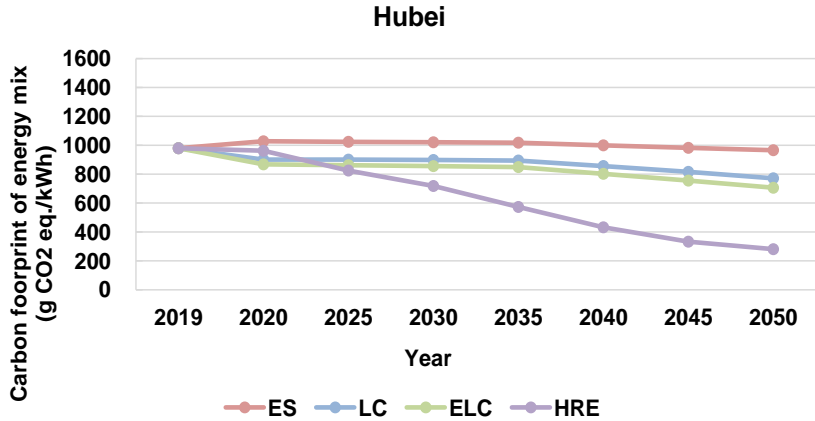


Figure 8: Carbon footprint of energy mix in Hubei

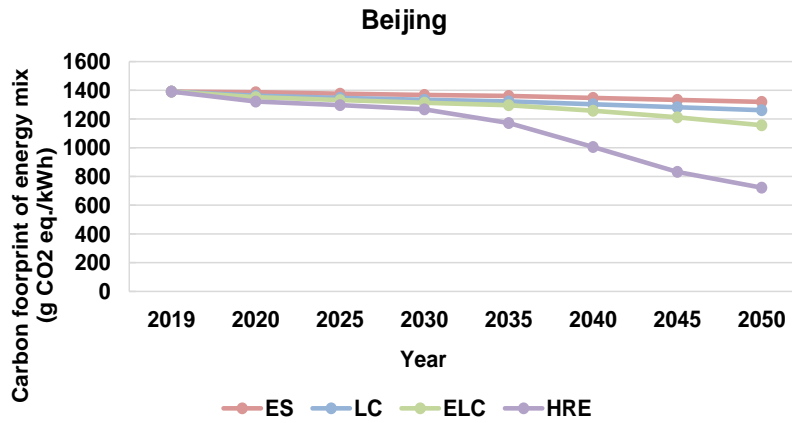


Figure 9: Carbon footprint of energy mix in Beijing

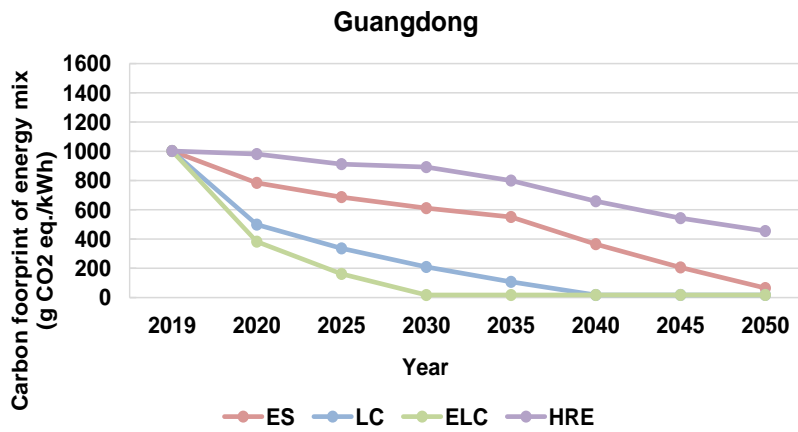


Figure 10: Carbon footprint of energy mix in Guangdong

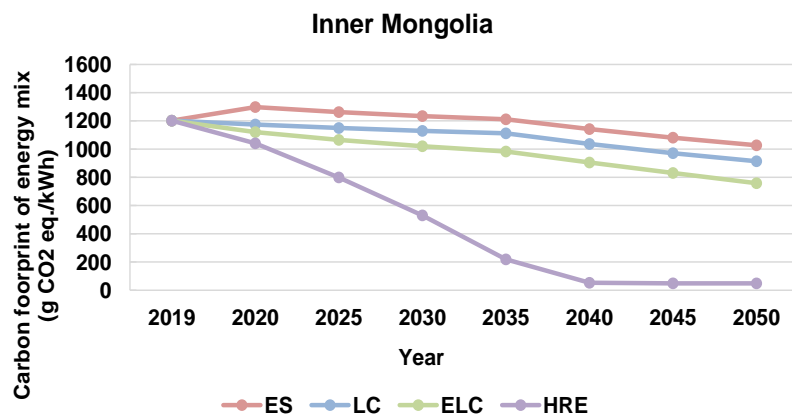


Figure 11: Carbon footprint of energy mix in Inner Mongolia

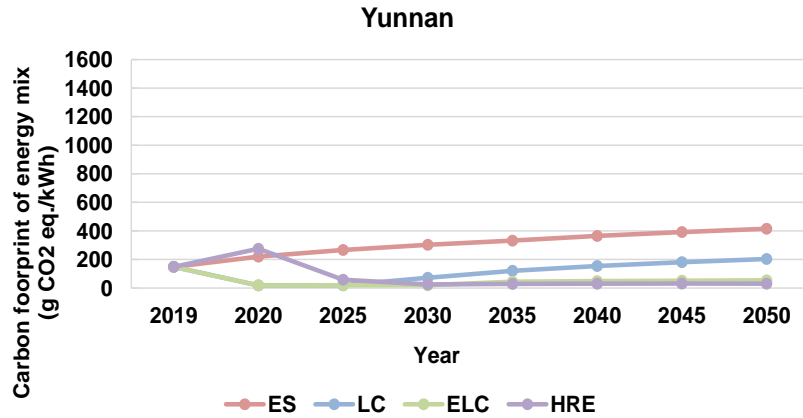


Figure 12: Carbon footprint of energy mix in Yunnan

4.2.2 Building materials

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.

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.

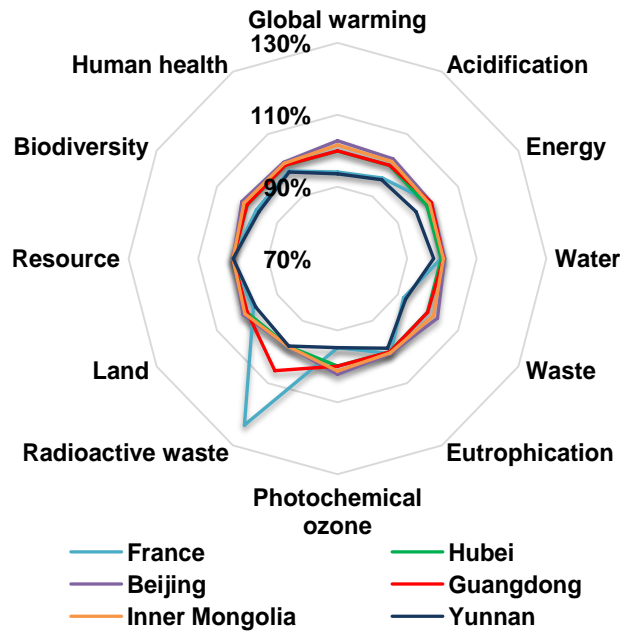


Figure 13: Effects of the construction stage with local energy mix 2019 compared to national average mix 2019 (NATION-2019)

4.3 Impacts of energy mix evolution scenarios

4.3.1 National static versus local static

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

Table 4: Evaluating system for the difference level

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

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

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

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

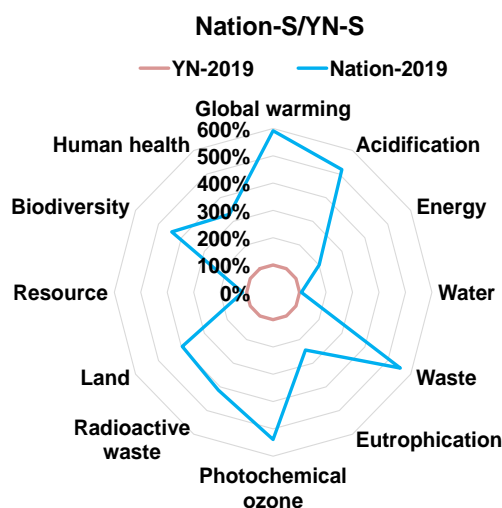


Figure 14: Impacts comparison of national average mix 2019 (Nation-2019) and Yunnan mix 2019 (YN-2019) for the use stage in Kunming, Yunnan

4.3.2 Local static versus local dynamic

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

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

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

Table 6: Impact differences of the use stage between using a local static mix and a local dynamic 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%

Table 7: Impact differences of the use stage between using a local static mix and a local dynamic 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%

Table 8: Impact differences of the use stage between using a local static mix and a local dynamic 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%

Table 9: Impact differences of the use stage between using a local static mix and a local dynamic 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%

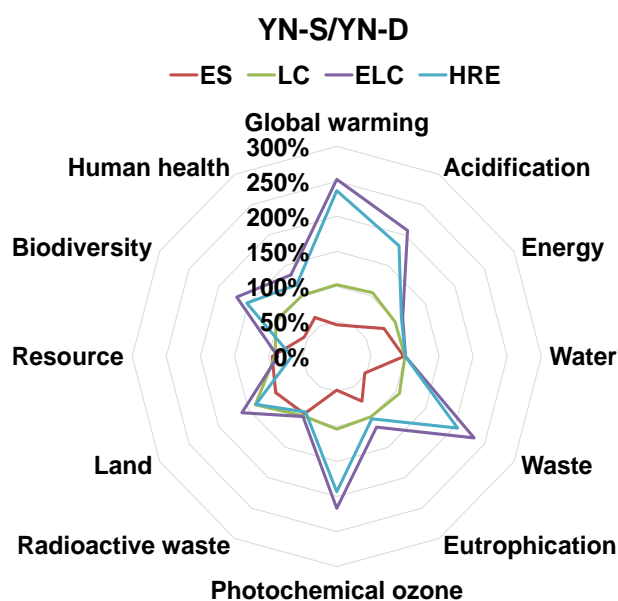


Figure 15: Impacts comparison of Yunnan static mix (YN-S) and Yunnan dynamic mix (YN-D) for the use stage in Kunming, Yunnan

4.4 Sensitivity analysis

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

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

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

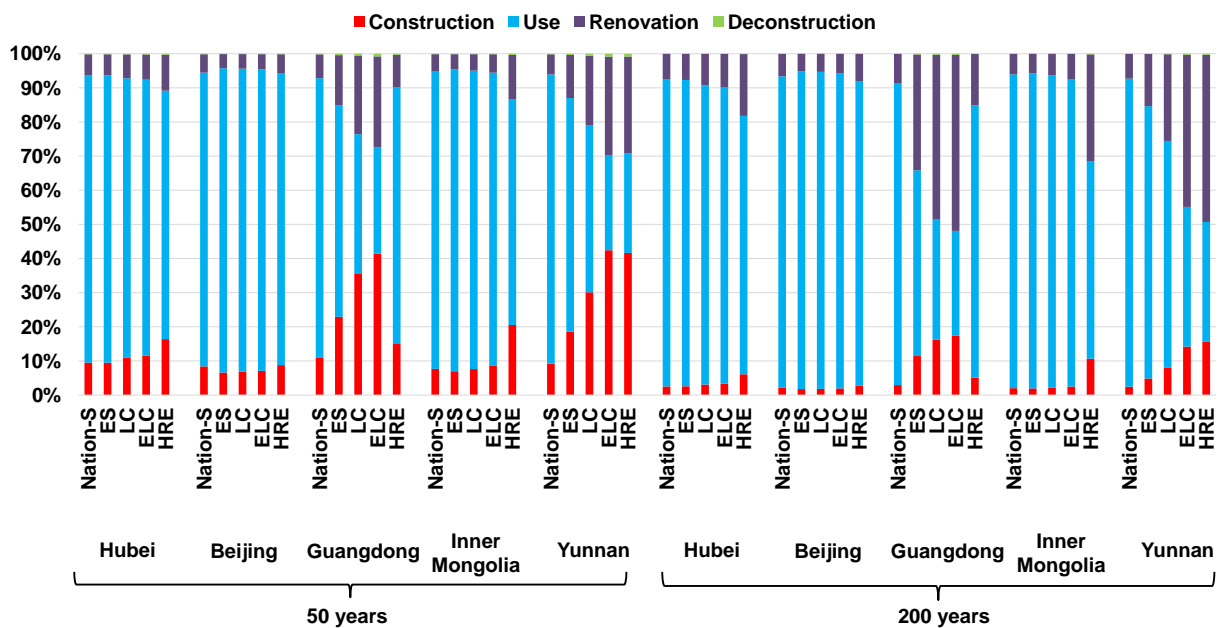


Figure 16: CO_{2eq} emissions share of each stage for a lifespan of 50 years and 200 years

5 . Conclusions and future research needs

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

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

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

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

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

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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 ”
$LCI_{\text{network},i}$	Life cycle inventory of the electricity network infrastructure per kWh for technology “ i ”

m	Technology index
n	Number of technologies
R	Ratio, %

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Superscripts and subscripts

FR	France
i	Technology index for nuclear or renewable technology (hydro, wind, solar)
j	Year
k	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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