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Caipeng Liang, Patrick Schalbart, Charlotte Roux, Bruno Peuportier. Enhancing life cycle assessment for reversible ground-coupled heat pump systems through dynamic analysis. *Journal of Cleaner Production*, 2024, 472, pp.143498. 10.1016/j.jclepro.2024.143498 . hal-04814742

HAL Id: hal-04814742

<https://hal.science/hal-04814742v1>

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Enhancing Life Cycle Assessment for Reversible Ground-Coupled Heat Pump Systems through Dynamic Analysis

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Abstract

Ground-coupled heat pump (GCHP) systems can provide comfortable indoor environments, but also inevitably contribute to greenhouse gas emissions and other impacts on human health, ecosystems, and resources. Life cycle assessment (LCA) methodology has been widely adopted to estimate the environmental impacts associated with GCHP systems, with operational electricity consumption being the largest contributor among most categories. Given the data-intensive nature of LCA, operational electricity consumption should be prioritised to refine the accuracy of LCA results. Previous studies, however, have relied on static COP (Coefficient of Performance) and annual average data to obtain the environmental impacts and have disregarded the effect of long-term performance degradation caused by building thermal load imbalances. In this paper, to bridge this research gap, a dynamic operational environmental impact assessment (DOEIA) method was proposed to improve the precision of LCA results by incorporating higher temporal resolution data of electricity mix and real-time performance modelling of the reversible GCHP system. Impacts of different temporal resolutions (i.e. monthly, trimestral, and annual) on the accuracy of LCA results was examined and the operational performance degradation resulting from imbalanced building heating and cooling loads was considered. Results demonstrate that while performance degradation effects are evenly distributed across impact categories, gaps due to temporal resolutions vary significantly between different categories. Subsequent analysis of spatial variations in the latter further emphasises the importance of accounting for higher temporal resolutions. Finally, life cycle impact

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22 assessment (LCIA) results for reversible GCHP systems in different locations were obtained with the support of
23 DOEIA method and the results underscore the necessity of a cleaner energy mix. The proposed DOEIA method can be
24 applied to other energy systems for comparative analyses. It is replicable in other countries and regions and therefore
25 is expected to provide methodological guidance for future decision-makers.

26 **Keywords**

27 Ground-coupled heat pump system; LCA; Environmental impacts; Electricity mix; Energy consumption

28 **1. Introduction**

29 The built environment significantly contributes to the global energy consumption and carbon emissions (Silva et
30 al., 2024). As the world's largest energy consumer and carbon emitter (IEA, 2021), China's building sector alone,
31 encompassing material production, construction, and operation, represents 46.5 % of the country's total energy
32 consumption and 51.3% of China's national carbon emissions (CABEE, 2020). Heating and cooling systems, with a
33 large share of up to 40 % in building total energy consumption (González-Torres et al., 2022), are undoubtedly
34 responsible for substantial carbon emissions. Given the accelerating pace of urbanization (Chang et al., 2017) and the
35 pursuit of carbon neutrality targets (IEA, 2021), increasing efficiency of heating and cooling systems as well as
36 reducing their emissions have become a major concern for energy conservation and environmental sustainability in
37 China (Lin and Liu, 2015). One major strategy is to promote the adoption of energy-efficient and eco-friendly systems
38 to meet thermal comfort requirements in buildings (Rosiek and Batlles, 2013).

39 Ground source heat pump is considered as one of the most promising heating and cooling technologies to realise
40 energy conservation and emission reduction. It benefits from reliable energy sources, stable operating conditions, and
41 easy maintenance, compared to other heating and cooling systems such as furnaces and air source heat pump (Chang
42 et al., 2017; Han et al., 2017) and therefore has experienced rapid growth and a widespread application all over China
43 (Zhu et al., 2015). Over the past two decades, installations of ground source heat pump in China have expanded more
44 than tenfold (J. Luo et al., 2023). China is now one of the leading countries for ground source heat pump in terms of
45 both installed capacity and annual energy use (Lund and Toth, 2021). Although ground source heat pumps offer an
46 alternative to fossil fuel infrastructure, they still contribute to greenhouse gas emissions and have other impacts on
47 human health, ecosystems, and resources.

48 LCA is currently recognised as one of the most comprehensive and robust approaches to evaluate environmental
49 impacts of products or services. It takes into account impacts during all stages of a life cycle in order to avoid transfer
50 of environmental impacts between stages, locations, and time periods (Finnveden and Potting, 2014). A lot of
51 researchers have used LCA to evaluate the environmental impacts associated with GCHP systems, and applications
52 were performed in China. It was shown that the electricity supply in the operation stage usually dominates
53 environmental impacts (Saner et al., 2010), and that the improvement of the electricity generation processes plays a
54 crucial role in mitigating the environmental impact on most impact categories (Zhai et al., 2022). As a result,
55 considering the data-intensive nature of LCA, electricity consumption, particularly during the operation stage, should
56 be prioritised to refine the accuracy of LCA results.

57 However, in previous LCA studies on GCHP systems, energy consumption for system operation is usually obtained
58 by dividing the annual building cooling and heating loads by the corresponding system performance factors (Violante
59 et al., 2022). In particular, the system performance factors at cooling and heating seasons are either estimated based
60 on measured data from other studies (L. Luo et al., 2023), directly using average values from previous studies (Wang
61 et al., 2020), using values obtained from software simulations of rated operating conditions (Aresti et al., 2021), or
62 using empirical values (Koroneos and Nanaki, 2017; Greening and Azapagic, 2012). The annual building loads are
63 generally identified through software (Kapıcıoğlu and Esen, 2022). Even though in some cases, onsite measured
64 electricity data was collected and utilized thanks to locally available projects (Zhang et al., 2022; Chang et al., 2017),
65 annual average electricity mix was considered to obtain subsequential environmental impacts without taking advantage
66 of real-time electricity consumption and considering the temporal variation of electricity mix over a year (Zhang et al.,
67 2020). Besides, some researchers were only concerned about a few specific environmental categories such as global
68 warming potential, acidification potential, eutrophication potential (Huang and Mauerhofer, 2016), life cycle climate
69 performance (Lee et al., 2023; Bae and Nam, 2022), or CO₂ emissions (Blum et al., 2010; Ren et al., 2018) instead of
70 conducting a comprehensive study based on an LCIA method. In addition, the degradation of the long-term
71 performance of GCHP system due to the imbalance of building cooling and heating loads, as a main issue of applying
72 GCHP system in different climate zones (Li et al., 2023), was not precisely modelled in LCA because the annual
73 electricity consumption of the system was assumed to remain the same during its lifespan (Saner et al., 2010).
74 Kapıcıoğlu and Esen (2022) mentioned the drop in GCHP performance caused by uneven loads, but it was ultimately
75 neglected due to the small size of the office building they studied and the low thermal imbalance ratio. At the spatial

76 scale, all above-mentioned studies focused only on a specific climate zone and did not consider the impact of changes
77 in the climate and electricity mix due to spatial variation on the environmental impacts. As a conclusion, all the above
78 low-resolution and mono-spatial estimates might lead to a loss of precision and generalisation in the LCA results and
79 their interpretation.

80 In recent years, a growing number of researchers have become aware of the influence of temporal and spatial
81 variations on the precision of LCA (Karl et al., 2019). It has been discovered that the dynamic results can be quite
82 different from the static results and the effects of dynamic variables on results can be positive or negative to various
83 degrees (Su et al., 2021). Many dynamic LCA studies, however, focused on the temporal variation of electricity
84 supply/production in buildings (Frapin et al., 2022; Karl et al., 2019) or distributed generation (Amor et al., 2014), or
85 on future-oriented dynamic assessments with emphasis on evolution of annual electricity mix (Pei et al., 2022a; Peht,
86 2006), and none of these studies shed light on the differences in environmental performance of energy systems such
87 as GCHPs applying high temporal resolution electricity consumption data, which is highly variable in terms of climate
88 conditions and system efficiency. Neirotti et al. (2020) performed detailed analyses of the electricity generation mix
89 and heat pump demand on an hourly time scale in the expectation of improving the common practice of assessing
90 energy consumption and emissions on an annual basis, but they did not target specific types of heat pump systems and
91 did not further analyse environmental impacts of heat pump systems, especially the energy consumption component.
92 Environmental impact assessment of an energy-efficient house in France has shown that using an annual average mix
93 can cause underestimation of potential impacts compared to hourly mix data results, with abiotic depletion being
94 underestimated by up to 39 % and global warming by up to 36 % (Roux et al., 2016). However, according to the IEA
95 real-time electricity tracker (IEA, 2022), the historical and real-time hourly and daily resolution data are not accessible
96 for China, as well as for many other countries. Yet a case study on domestic hot water production systems (Beloïn-
97 Saint-Pierre et al., 2017) demonstrated that considering different temporal precision (i.e., monthly vs. annual) for
98 energy consumption as well as other process flows can lead to opposite conclusions in determining which case exhibits
99 superior environmental performance. As a result, given that power supply changes over months and seasons, it is still
100 valuable to evaluate the environmental impacts of GCHP systems accounting for monthly temporal variations. Besides,
101 since the climate and natural resources differ in various Chinese provinces, the impact of different heating/cooling
102 loads and electricity mixes due to geographical variability should also be examined.

103 To fill the abovementioned gaps in the literature, a dynamic operational environmental impact assessment (DOEIA)
104 method was proposed and applied in this paper. The novelty of the study lies in enhancing the accuracy of LCA results
105 by incorporating higher temporal resolution data in three dimensions: the electricity mix, the system COP, and the
106 building load. Furthermore, benefiting from the methodology, the effect of long-term performance degradation on
107 environmental impacts due to imbalance of building heating and cooling loads can be integrated, evaluated, and
108 explained. Another innovative aspect of this work is the comparison of the effect of different temporal resolutions
109 (monthly, trimestral, and annual) on the precision of operational environmental impacts, and the elucidation of the
110 mechanism behind the differential distribution of this effect across various impact categories. Finally, the overall
111 environmental impacts of applying the GCHP system in different climatic zones were evaluated through LCA using
112 the more accurate DOEIA method. This study can be extended to comparative analyses of different energy systems in
113 other countries and regions and is expected to offer methodological guidance for decision-makers.

114 **2. Materials and methods**

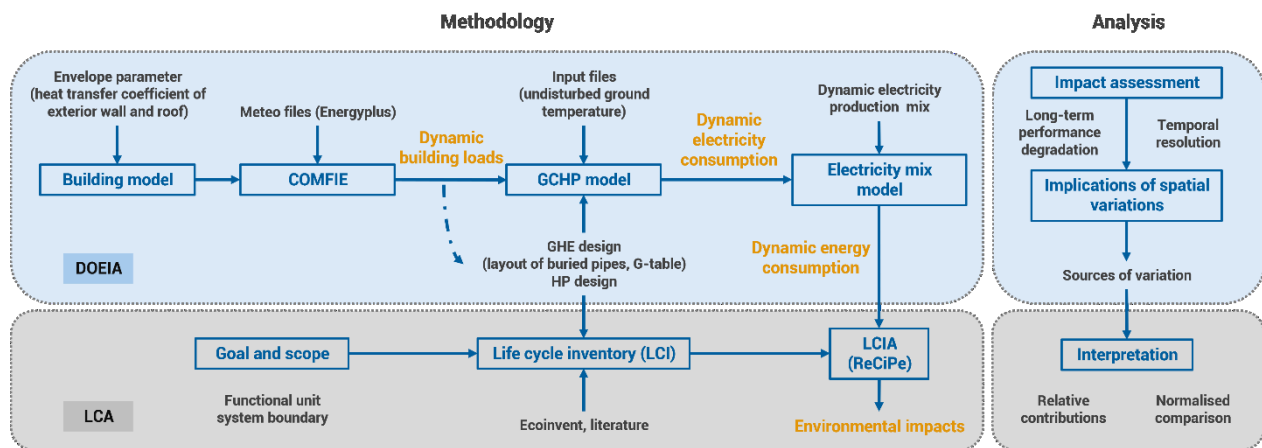
115 *2.1. Overall methodology*

116 The environmental impact assessment method in this study can be divided into two main parts: one focusing on
117 the impact of electricity consumption during the operational stage and one focusing on the impact of the other phases
118 of the system. In order to improve the precision of the environmental impact assessment of energy systems, this study
119 focused on the significant part of the operational energy consumption of the system and applied a dynamic approach
120 (DOEIA) to enhance the temporal resolution of the building load side, the system energy efficiency side and the
121 electricity production side. The effects of temporal resolution and long-term performance degradation were first
122 analysed under climatic conditions of Wuhan (China). Afterwards, to better interpret sources of variation caused by
123 adopting different temporal resolutions, the method was applied to several representative cities of climate zones in
124 China. For each city, relevant thermal parameters of the envelope (GB 55015, 2021) and the meteorological conditions¹
125 were introduced in building simulation tool COMFIE to evaluate the building loads. On this basis, the ground heat

¹ https://energyplus.net/weather-location/asia_wmo_region_2/CHN

126 exchanger (GHE) and heat pump (HP) were designed to control the outlet temperature of the GHE within specified
 127 limits (GB50366, 2009) and to ensure proper operation of the HP. The corresponding parameters were entered into the
 128 GCHP model. After the simulation, electricity consumption of the GCHP system was obtained and environmental
 129 impacts were derived according to the chosen LCIA methodology, as displayed in Fig. 1. Building heating/cooling
 130 loads and electricity production mix varies between provinces, which allowed us to examine how environmental
 131 impacts depend on site-specific characteristics, and thus influence the comparison between GCHP and other systems
 132 for buildings.

133 The environmental impacts of electricity consumption based on the abovementioned DOEIA method were added
 134 to the impacts of the other life cycle stages to get total environmental impacts of the GCHP system in different contexts.
 135 Further analysis of the results was conducted in terms of both relative contributions and normalized comparisons. The
 136 framework of the overall methodology and analysis is shown in Fig. 1. Specific models involved in the proposed
 137 DOEIA method are explained in Section 2.2. Then, following the LCA framework outlined in the ISO 14040 standard
 138 (ISO, 2006, p. 140), each of these steps, namely goal and scope, life cycle inventory (LCI), and life cycle impact
 139 assessment (LCIA), is elaborated sequentially in Section 2.3. Finally, the case study and corresponding parameter
 140 settings are presented in Section 2.4.

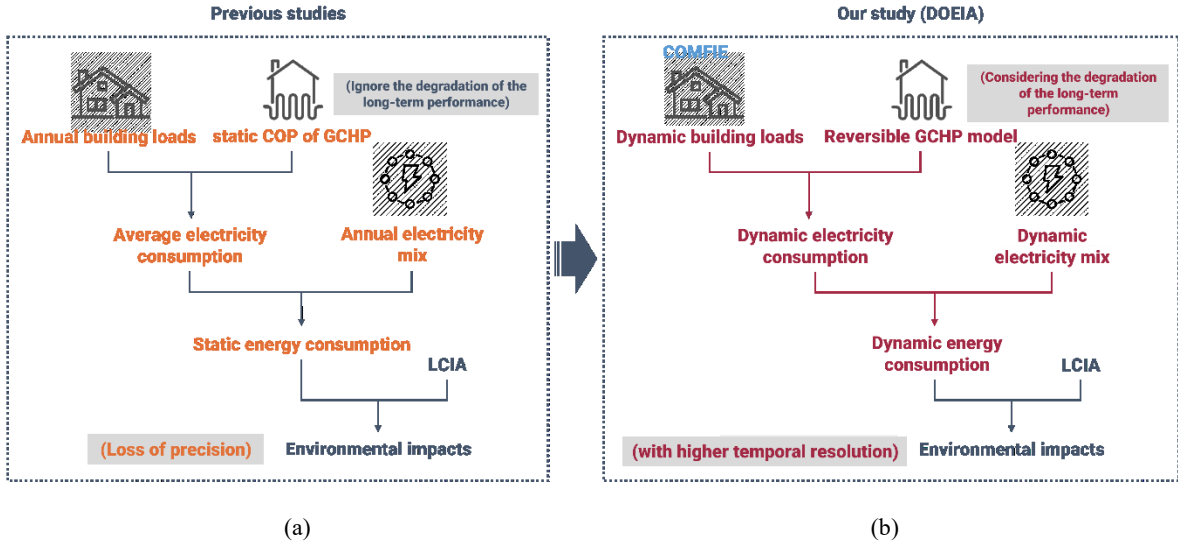


142 **Fig. 1.** The framework of the overall methodology and analysis.

143 *2.2. Dynamic operational environmental impact assessment method (DOEIA)*

144 As mentioned above, environmental impacts of electricity consumption during the operational stage have been
 145 proven to be the largest contributor to almost all categories. However, previous studies, as shown in Fig. 2(a), have
 146 only utilised a static COP, annual average building loads, annual national or provincial electricity mix to generate

147 energy consumption and final environmental impacts, and have also failed to account for long-term performance
 148 degradation. Therefore, to increase the precision of the LCA, environmental impacts of electricity consumption will
 149 be independently analysed using a dynamic method, through which interactions between buildings and the GCHP
 150 system including the long-term performance fluctuation caused by building seasonal imbalance were considered. The
 151 process to evaluate environmental impacts of electricity consumption based on dynamic electricity data is displayed
 152 in Fig. 2(b).



153
 154 **Fig. 2.** (a) Previous static data-based method and (b) proposed DOEIA method to assess environmental impacts of operational
 155 electricity consumption in GCHP systems.

156 To be more specific, the building model is created in the building simulation software COMFIE (Peuportier and
 157 Blanc-Sommereux, 1990) to generate hourly building loads of the studied buildings according to the building envelope,
 158 HVAC (heating, ventilation and air-conditioning) equipment, local meteorological conditions, occupancy, and internal
 159 gains. A reversible GCHP model, consisting of a parameter estimation-based steady state semi-empirical model of
 160 water-to-water heat pump with rotary compressor (Filliard et al., 2009; Jin and Spitler, 2003) and a global model of
 161 large-scale boreholes heat exchangers (Pei et al., 2022b), was then integrated into COMFIE so that electricity
 162 consumption can be derived on the basis of real-time energy efficiency of the system at each timestep. The heat pump
 163 system can be described with a few parameters regarding compressor, heat exchangers, and expansion valve (Liang et
 164 al., 2023). The borehole heat exchanger model is combined with the finite line source model, the 2D heat equation and
 165 a three-points method (Pei et al., 2022b). Following this, the long-term energy consumption can be calculated based

166 on the dynamic electricity production mix of the region where the project is located. Finally, the environmental impacts
 167 of electricity consumption can be derived from the life cycle impacts of different electricity production technologies.

168 From hourly electricity consumption obtained using COMFIE and a GCHP model, environmental impacts of the
 169 total power consumption $EI_{total,electricity}$ over the 20-year operation stage can be quantified by aggregating the energy
 170 consumption per technology per unit timestep weighted by the environmental impact of 1kWh electricity produced by
 171 each technology, as expressed in Eq. (1):

$$EI_{total,electricity} = \sum_{t=1}^k \sum_{i=1}^{ll} (E_t \times R_{i,t} \times I_i) \quad (1)$$

172 where i represents a given power generation technology, t represents the t th time step in the total time steps k during
 173 the system operation stage, E_t represents electricity consumption of reversible GCHP system at timestep t , $R_{i,t}$
 174 represents the share of technology i at timestep t .

175 Life cycle impacts of 1 kWh delivered to the low voltage level (below 1 kV) by a given technology, I_i , include
 176 impacts related to electricity production using the technology and impacts related to the network infrastructure (Roux
 177 et al., 2016), as indicated in Eq. (2):

$$I_i = C_f \times (LCI_i \times (1+l) + LCI_{network,i}) \quad (2)$$

178 where C_f is the characterisation factor matrix, LCI_i is the life cycle inventory of one kWh produced by technology “ i ”,
 179 $LCI_{network,i}$ is the life cycle inventory of electricity network infrastructure per kWh supplied in the studied region for
 180 technology “ i ”, and l is the level of losses. l represents electricity lost during transmission in the transport network
 181 (national and interconnection high voltage network), conversion, and transmission in the distribution network (national
 182 low and medium voltage network, below 24 kV). 2 % losses are accounted for the transport network and 4 % losses
 183 for the distribution network (Pei et al., 2022a).

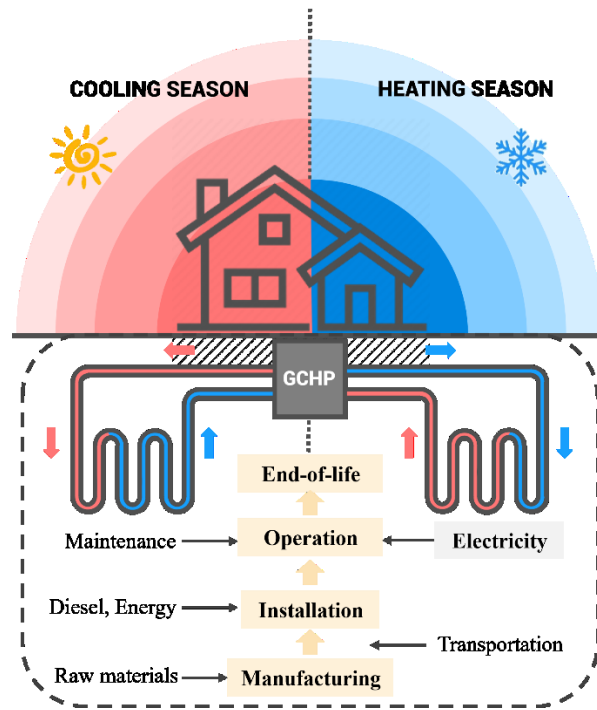
184 2.3. Life cycle assessment

185 2.3.1. Goal and Scope

186 The goal of this LCA study is to compare GCHP with other heating and cooling systems. This comparison was
 187 performed considering a specific case study, corresponding to an apartment building in China (see §2.6). Comparative
 188 LCA requires evaluating main uncertainties, which are therefore also addressed.

189 A reversible ground-coupled heat pump system, as the most commonly employed ground source heat pump type
 190 in China (Zhou et al., 2016), was selected to meet the heating and cooling needs of the studied buildings. The life span

191 of the heat pump was assumed to be 20 years (Greening and Azapagic, 2012). The functional unit was therefore defined
 192 as providing heating and cooling that maintains the indoor temperature of the building between 18 °C and 26 °C for
 193 20 years. The system boundary of the reversible GCHP system includes manufacturing, installation, operation, and
 194 end-of-life stages, as illustrated in Fig. 3. Terminal units were not modelled because they are not specific to GCHP
 195 systems. When evaluating the energy consumption of the building, a radiant floor system was considered, and
 196 distribution losses were neglected (i.e. 100 % efficiency).



197
 198 **Fig. 3.** System boundary.

199 **2.3.2. Life cycle inventory (LCI)**

200 **2.3.2.1 Electricity production mix profile in China**

201 Electricity production mix plays a paramount role in the dynamic approach applied in this paper. Considering the
 202 diversity of China's climates attributed to its vast territory, intricate topography, geography, natural resources and the
 203 influence of the surrounding ocean, the climate as well as the electricity production mixes vary significantly in the
 204 different regions. The monthly electricity production mix in all five typical cities can be found in Fig. A1 and Fig. A2
 205 of Appendix, based on the data collected from National Bureau of Statistics (2022). Thermal power dominates in most
 206 cities, with an average annual percentage of 80.2 %, 97.3 %, and 74.1 % in Harbin, Beijing, and Shenzhen, respectively.

207 Electricity mix of Wuhan varies from month to month, but is dominated by thermal and hydropower production, with
208 average annual proportions of 50.8 % and 42.7 % respectively. Kunming differs significantly from the other cities, the
209 mix being dominated by hydropower, with an average annual proportion of 78.4 %. It is noteworthy that Shenzhen is
210 the only city with a significant share of nuclear energy (19.6 % on average) and Harbin has an average of 13.7 % of its
211 electricity coming from wind power.

212 When it comes to electricity production, only photovoltaic systems are considered to release power at low voltage,
213 all other technologies are considered to produce electricity at high voltage (above 24 kV). The share of coal, oil, and
214 gas in thermal power generation in the five cities is assumed to be equal to the national share (National Bureau of
215 Statistics, 2022). The proportion of different technologies in each energy source is assumed to be identical during the
216 system operation stage. Detailed technologies of five typical cities and their corresponding shares are listed in Table
217 A1 of Appendix.

218 Ecoinvent v3.4 database provides life cycle inventories (i.e. quantities of raw materials used, pollutants emitted to
219 the air, water, and ground) corresponding to 1 kWh of electricity produced by different technologies at high voltage
220 level (above 24 kV) for different provinces of China. It also includes inventories for grid infrastructure (transmission
221 and distribution network) (Treyer and Bauer, 2016).

222 *2.3.2.2 Inventory of the reversible GCHP system*

223 Data regarding the manufacturing and installation phases of reversible GCHP system was acquired from different
224 sources. In particular, datasets of heat pump and ground heat exchanger provided by Ecoinvent (Wernet et al., 2016)
225 were used as a basis and were then contextualised with custom and calculated data sources (Luo et al., 2022; Saner et
226 al., 2010). Refrigerant R410a which comprises 50 % difluoromethane and 50 % pentafluoroethane was chosen as the
227 working fluid in refrigeration cycle of reversible GCHP systems due to its high proportion in new heat pumps (Kägi
228 et al., 2021) and its advantages of minimising pressure drop (Fannou et al., 2015). Considering that there is no available
229 inventory of difluoromethane and pentafluoroethane as material inputs (technological flows) for the refrigerant,
230 trifluoromethane and difluoroethane, respectively, were used as approximations. But it is worth noting that
231 difluoromethane and pentafluoroethane are present in the biosphere database and, consequently, were directly emitted
232 into air as elementary flows (Kägi et al., 2021). Furthermore, the average refrigerant loss rate was considered to be 3 %
233 during the manufacturing phase and 19 % during the disposal phase of the heat pump, resulting in a total of 22 % losses
234 accounted for as emissions into the air (Kägi et al., 2021). As for the operation phase, 6 % losses per year are considered

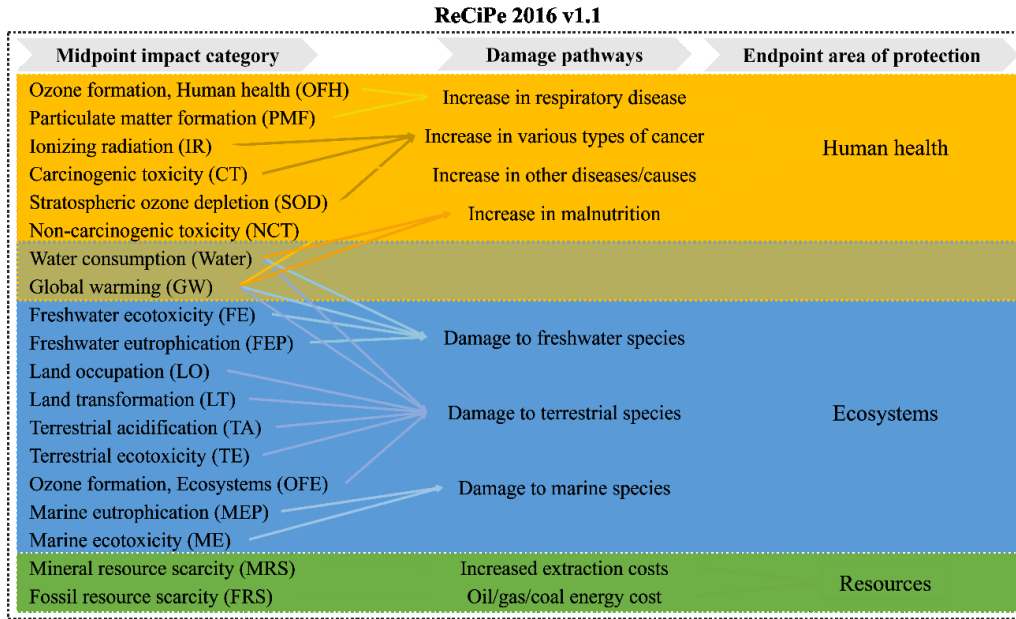
235 (Luo et al., 2022). The heat collector for the GCHP system includes both vertical and horizontal high-density
236 polyethylene (HDPE) pipes that connect the wellhead to the heat pump (Violante et al., 2022). Detailed material
237 inventory for components of the reversible GCHP system is reported in Table A2.

238 Standard transport distances from Ecoinvent v3.4 database (Wernet et al., 2016) were used in this study. For the
239 operation phase, electricity consumption data was collected through the reversible GCHP model integrated into the
240 dynamic building energy simulation (DBES) software COMFIE. The weather files in the five cities were downloaded
241 from EnergyPlus website². The hourly building heating and cooling loads can then be obtained and correspondingly
242 converted into the dynamic electricity consumption of the system. Only the end-of-life phase of heat pump was
243 considered in this study, as the technical lifespan of ground heat exchangers and heat collectors were assumed to be
244 100 years, which is beyond the scope of the 20-year study. Metal parts of the heat pump were recycled, as well as 81 %
245 of the refrigerant.

246 2.3.3. *Life cycle impact assessment (LCIA)*

247 In this study, the assessment of environmental impacts was conducted using the ReCiPe 2016 v1.1 method
248 (Huijbregts et al., 2016) considering a hierarchist perspective. This method is an updated version of ReCiPe 2008
249 (Goedkoop et al., 2008) and is more appropriate for environmental impact assessment on a global scale. The overview
250 of the relation between the midpoint impact categories and the three areas of protection in the ReCiPe 2016 v1.1
251 methodology is displayed in Fig. 4.

² https://energyplus.net/weather-location/asia_wmo_region_2/CHN



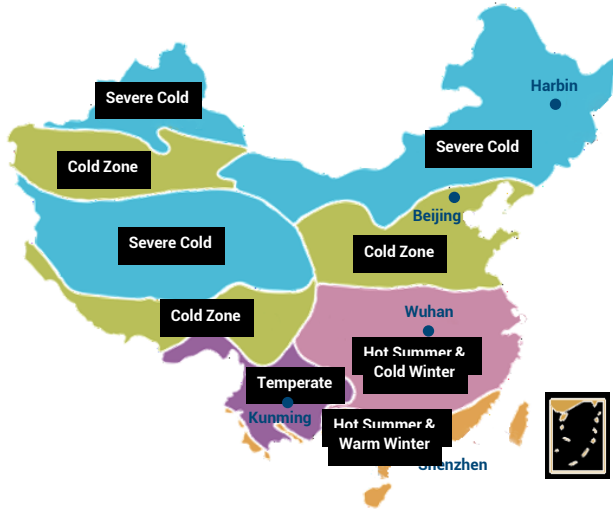
252

253

Fig. 4. Overview of the impact categories in ReCiPe2016 v1.1 methodology and their link to the areas of protection.

254 *2.4. Case study*

255 Climate conditions, energy needs, and electricity production mix vary according to the location of the studied
 256 system. The Chinese national standard "Code for Thermal Design of Civil Buildings (GB50176, 2016)" divides China
 257 into five climate zones: severe cold, cold, hot summer and cold winter, hot summer and warm winter, and temperate,
 258 using outdoor air temperature as the primary indicator. This division is intended to provide guidance for the design of
 259 the thermal properties of the building envelope in each specific climate zone and identifies the major cities in that
 260 climate zone. One representative city in each climate zone is selected in this study, namely Harbin, Beijing, Wuhan,
 261 Shenzhen, and Kunming, as illustrated in Fig. 5(a). The abovementioned dynamic method was first applied to Wuhan,
 262 a city belonging to "hot summer and cold winter" climate zone with both high heating and cooling demands throughout
 263 the year, which makes it an ideal region for the application of GCHP systems. After a preliminary analysis of the
 264 relative impacts induced by using different time resolutions and long-term performance degradation in Wuhan, a
 265 representative city within each of the other four climatic zones was chosen to conduct a manageable sensitivity analysis
 266 considering environmental impacts as output and typical geographical locations with different meteorological
 267 conditions and electricity production mixes as input parameters.



(a)



(b)

268 **Fig. 5.** (a) Five climate zones and relevant typical cities and (b) the studied residential building model in China.

269 A residential block consisting of 4 collective buildings, as a common residential building type in China (Song et
 270 al., 2024), was assumed to be geometrically identical in all five locations. Each building has 34 floors and is 100 meters
 271 high, with a total building area of 64,910 m². The occupancy was set as 0.02 person/m² from 8h00 to 17h00 from
 272 Monday to Friday and 0.04 person/m² for the rest of the time. Only one residential building in the block was simulated
 273 as a sample building using COMFIE, as displayed in Fig. 5(b). Dynamic hourly building loads identified from this
 274 sample building were then scaled up with a multiplier four to approximately represent the total loads of the four
 275 residential buildings in the block. Load profile of buildings and thermal imbalance ratios in five typical cities are
 276 displayed in Table A3 of Appendix. The detailed parameters of GCHP system in the five locations are listed in Table
 277 A4 of Appendix. Among them, the demand for HP is determined by the maximum heating/cooling power in a year,
 278 while the electricity consumption is mainly determined by the accumulated heating/cooling load of the building and
 279 the efficiency of the GCHP system. As for the demand for GHEs, it is mainly determined by the accumulated heat in
 280 the ground and the thermal imbalance ratio in a year. Specifically, according to the process shown in Fig. 1, the dynamic
 281 building loads can be obtained from the building simulation tool COMFIE, followed by further simulation of the heat
 282 extracted/released from/to the ground over the course of a year based on the heat pump model mentioned in Section
 283 2.2. Finally, the layout of the GHEs (number, depth, distance, etc.) is determined through iterations based on the
 284 borehole heat exchanger model (Pei et al., 2022b). The ultimate goal of the iteration is to obtain the optimal solution
 285 that satisfies the national standard (GB50366, 2009) for the inlet and outlet temperatures of the GHEs in order to ensure

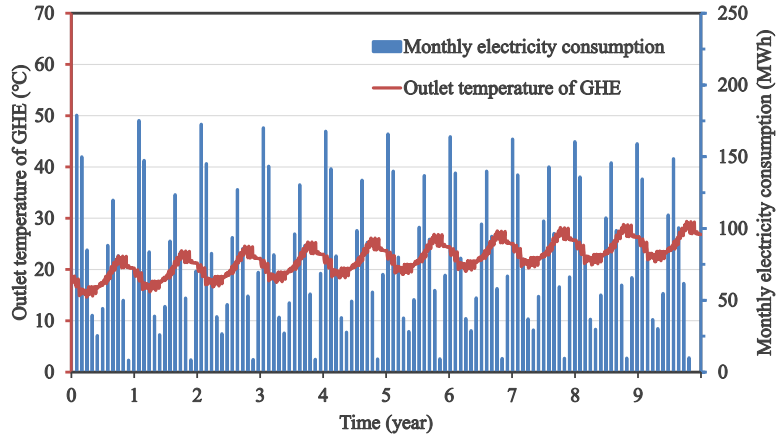
286 the proper operation of the heat pump and to minimise the initial investment cost. Considering the lower sensitivity of
287 vertical GHE to ground surface temperature and the smaller land area covered compared to horizontal GHE (Yuan et
288 al., 2012), vertical GHE with double U-tubes in each borehole was used in this study.

289 **3. Results**

290 *3.1. Impact assessment of operational electricity consumption based on dynamic electricity production mix data*

291 *3.1.1. Long-term performance of reversible GCHP system*

292 The reversible GCHP system is more suitable for applications in climate zones where buildings have close balanced
293 heating and cooling loads. Therefore, based on the building load profiles and thermal imbalance ratios shown in Table
294 A3 in the Appendix, Wuhan was first selected as a representative city for the preliminary study. The annual heating
295 and cooling loads under Wuhan conditions are 2,577 MWh and 2,798 MWh respectively, corresponding to annual
296 heating and cooling loads per unit area of 51 kWh/m² and 55 kWh/m². The peak heating and cooling power are 2,627
297 kW and 2,096 kW, respectively. The outlet temperature of GHE and monthly electricity consumption of the reversible
298 GCHP system are shown in Fig. 6. It can be found that the ground temperature increases over the years, leading to
299 decreasing electricity consumption in heating seasons and increasing electricity consumption in cooling seasons.
300 Despite the fact that the ratio of heating and cooling loads is close to 1, the GHE discharges more heat to the ground
301 than it absorbs throughout a year because the heating load and COP are higher than cooling load and COP, which
302 makes the ground temperature increase over the years. This temperature rise increases the efficiency of the GCHP
303 during the heating season and decreases the performance during the cooling season. Therefore, there is a year-on-year
304 reduction in electricity consumption during heating seasons, but a slight increase during cooling seasons. It should be
305 noted that due to the relatively large diameter of double U-tubes (0.05 m of external diameter and 0.04 m of internal
306 diameter), the electricity consumption of the circulating pump on the GHE side is almost negligible (less than 1 %)
307 due to the low pressure drop in the GHE.



308
309

Fig. 6. Outlet temperature of GHE and monthly electricity consumption of reversible GCHP system.

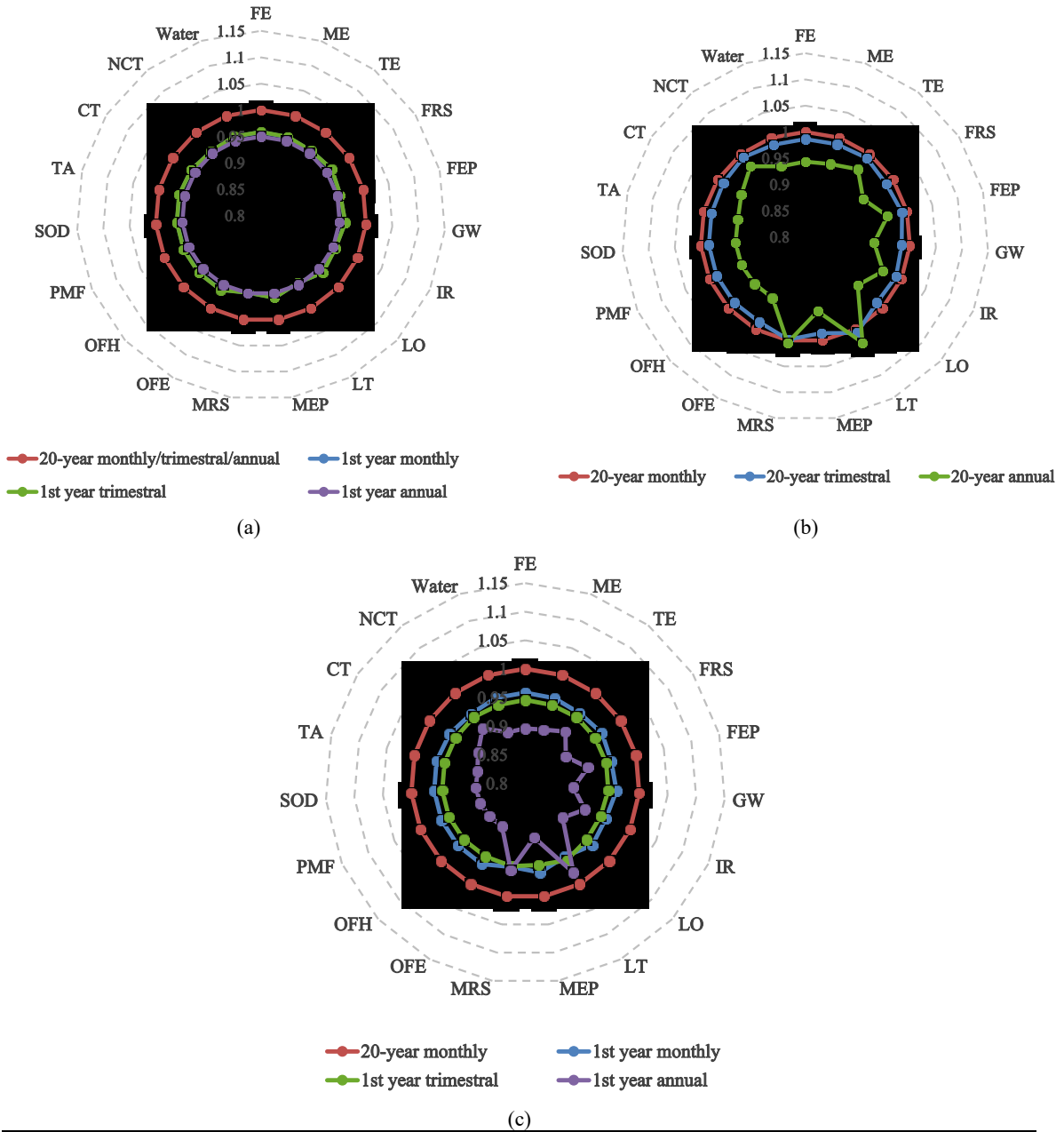
310 *3.1.2. Effects of long-term performance degradation and temporal resolution on environmental impacts of electricity*
311 *consumption in the GCHP system*

312 In order to evaluate the effect of long-term performance degradation of the GCHP system, LCA results using only
313 one-year energy consumption data and the 20-year energy consumption data were firstly compared, as displayed in
314 Fig. 7(a). Detailed values in Fig. 7 can be found in Table A5 of the Appendix. Monthly electricity mix in 2022 was
315 selected and assumed to be identical over the 20-year operation stage of the GCHP system. Environmental impacts
316 calculated using 1st year annual/trimestral/monthly energy consumption data were separately compared with
317 environmental impacts calculated using 20-year annual/trimestral/monthly energy consumption data. At the same
318 temporal resolution, the results for environmental impacts exhibit similar levels of underestimation for all midpoint
319 categories, with monthly, trimestral, and annual underestimation averages of 4.3 %, 4.2 %, and 5.0 %, respectively.
320 The reason for this is that, under the assumption that the annual electricity mix does not evolve over time, once the
321 temporal resolution has been determined, the performance degradation has an equal influence on each of the impact
322 categories of electricity consumption within the same time-step interval for each year. Taking August at monthly
323 temporal resolution as an example, the electricity consumption in August increases sequentially for each of the 20
324 years, but since the electricity mix and the generation technology used are assumed to remain the same in August each
325 year, the value of each impact category for the electricity consumption in August of each year decreases in the same
326 proportion compared to the previous year. Thus, the impacts brought about by long-term performance degradation after
327 the final cumulative 20 years are also uniformly distributed across the impact categories.

328 The comparison of environmental impacts over 20-year using monthly/trimestral/annual time steps is then shown
329 in Fig. 7(b) for all midpoint categories to explore the effect of different temporal resolutions. The results using monthly
330 electricity mix and monthly electricity consumption data (over 20 years) were supposed to have the highest accuracy
331 and therefore considered as a reference for comparison. It should be noted that coordinates selected for the radar plots
332 in this study range from 0.8 to 1.15 to better observe the variation of each category. It can be observed that the gap
333 between results using 20 years of trimestral data and 20 years of monthly data is insignificant. However, when using
334 20 years of annual data to quantify the environmental impacts, the discrepancy in outcomes begins to become
335 significant. All categories other than LT (Land Transformation) and MRS (Mineral Resource Scarcity) were
336 underestimated, ranging from 3.0 % (Non-carcinogenic Toxicity) to 6.8 % (Global Warming), with an average
337 underestimation of 5.6 %. It is apparent that the reasons of the effects of different temporal resolutions on different
338 impact categories appear to be more complex than those caused by long-term performance degradation. This could be
339 related to fluctuations in electricity mix and power consumption over time as a result of seasonal influences and is
340 therefore explored in further depth later in Section 3.2.

341 If both effects are considered together, an aggregated comparison involving the effects of long-term performance
342 degradation and different temporal resolutions was also conducted, as shown in Fig. 7(c). It was shown that compared
343 to the results with 20-year monthly energy consumption data, using 1st year monthly and trimestral energy consumption
344 data leads to an average underestimation of 4.3 % and 5.4 % respectively, for all midpoint categories. It is noteworthy
345 that using annual data from the 1st year results in an average underestimation of 9.6 % for all midpoint categories, with
346 the largest underestimation being 11.5 % for category GW (Global Warming).

347 In summary, due to its simple cumulative nature, the effects caused by long-term degradation are similar across
348 different midpoint categories. Furthermore, if other additional equipment is utilised to balance the heating and cooling
349 loads of the reversible GCHP, the ground temperature could be better controlled and thus the long-term performance
350 degradation can be considerably weakened in some cases. However, the gaps caused by different temporal resolutions
351 are relatively larger and vary substantially across different impact categories. Therefore, it is necessary to further
352 analyse the effect of temporal resolution on environmental impacts in different contexts to provide guidance for
353 subsequent studies.



354 Fig. 7. Impacts comparison of electricity consumption (a) with/without considering long-term performance degradation (same
 355 temporal resolution); (b) with monthly/trimestral/annual time steps; (c) with/without considering long-term performance
 356 degradation (different temporal resolution).

357 *3.2. Implications of spatial variations on the environmental impact of operational energy consumption*

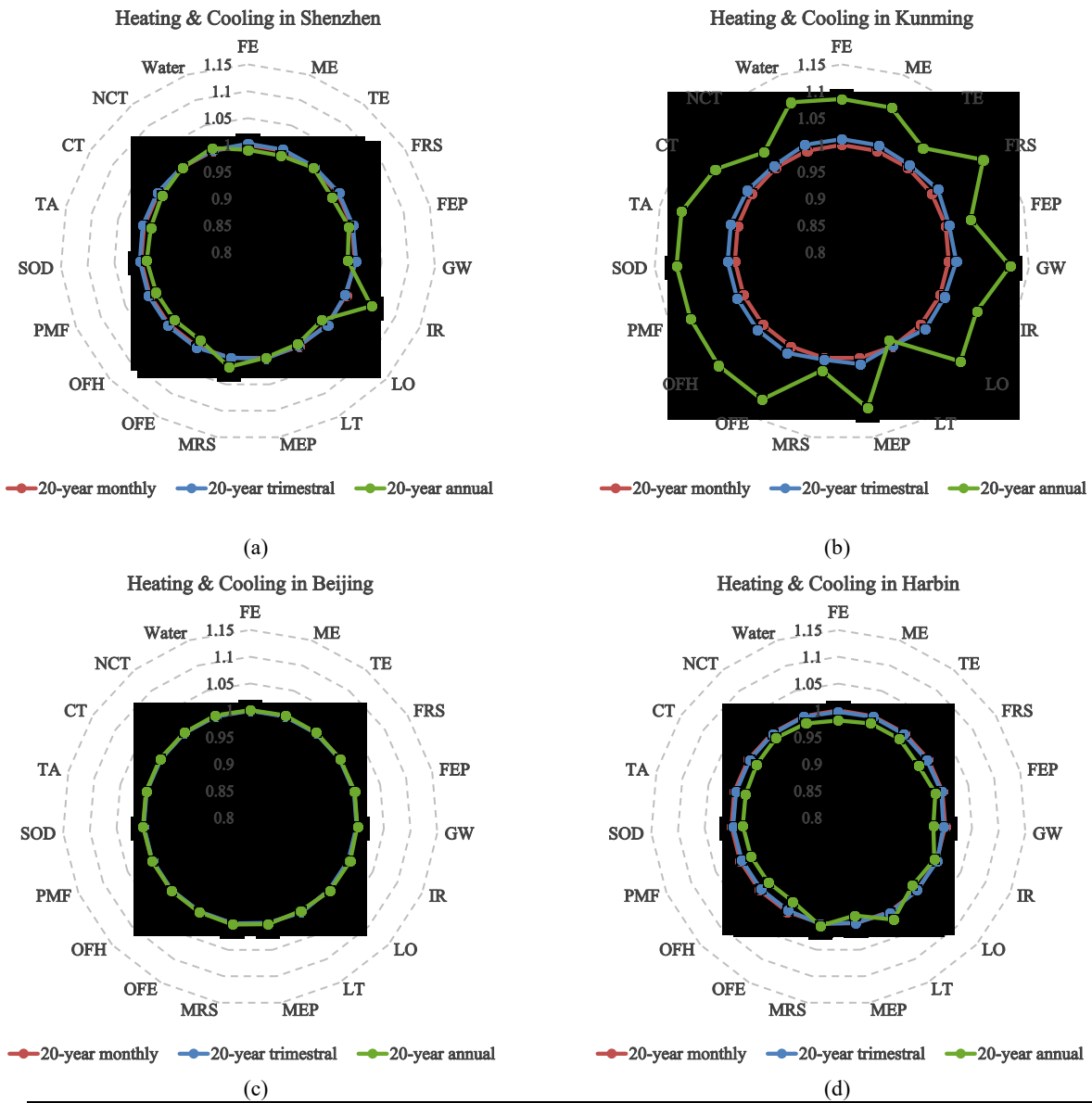
358 To better observe how spatial variations of dynamic electricity mix and energy consumption affect the
 359 environmental impacts of the reversible GCHP system, the same study was performed for the other four typical cities
 360 in China, as mentioned above in Fig. 1. Fig. 8 displays a comparison of environmental impacts over a 20-year period
 361 using monthly, trimestral, and annual time intervals in four cities for all midpoint categories. Detailed values in Fig. 8
 362 can be found in Table A6 of the Appendix. Due to the significant variation in the electricity mix (see Table 1 and Fig.
 363 A1) as well as in the climatic conditions (Fig. 5(a)) of the different regions, the gaps in environmental impacts obtained
 364 from using different temporal resolutions exhibit distinct spatial differences. Overall, the discrepancy between results
 365 using 20 years of trimestral data and 20 years of monthly data is insignificant in all four locations.

366 **Table 1** Annual electricity mix in five locations (National Bureau of Statistics, 2022).

	Coal	Oil	Natural gas	Hydro	Wind	Solar	Nuclear
Wuhan	44.94 %	4.43 %	4.09 %	39.9 %	4.41 %	2.24 %	0 %
Shenzhen	61.44 %	6.05 %	5.59 %	2.81 %	4.23 %	0.95 %	18.92 %
Kunming	10.23 %	1.01 %	0.93 %	81.1 %	5.75 %	0.97 %	0 %
Beijing	82.13 %	8.09 %	7.48 %	1.91 %	0 %	0.39 %	0 %
Harbin	65 %	6.4 %	5.92 %	2.64 %	16.17 %	3.87 %	0 %

367

368 When using the 20 years of annual data rather than monthly data to derive environmental impacts, all categories in
 369 Beijing remained virtually unchanged and the gaps in Harbin were negligible as well. Gaps were still acceptable in
 370 Shenzhen for all categories except IR (Ionizing Radiation), which was overestimated by 5.1 %. However, the gap
 371 profile of Kunming is quite different, with eight midpoint categories featuring overestimations higher than 10 % (FRS,
 372 GW, LO, OFE, OFH, PMF, SOD, and TA) and five midpoint categories featuring overestimations higher than 8 % (FE,
 373 ME, MEP, CT, and Water), resulting in an average overestimation of 8.1 % across all categories. It can be concluded
 374 that the gap between results corresponding to different temporal resolutions depends on the location and impact
 375 category. However, there is no clear pattern in the variation of this gap among all five cities. Based on Eq. (1), it can
 376 be understood that the environmental impacts are a combination of the electricity mix $R_{i,t}$, the consumption of each
 377 technology E_t , and its life cycle impacts I_t . Therefore, in the following two subsections, different components will be
 378 analysed in depth to identify the sources of gap between different temporal resolutions and attempt to quantify them.



379 **Fig. 8.** Impact assessment of 20-year electricity consumption with monthly/trimestral/annual time steps in five typical cities.

380 *3.2.1. Time-scale gap of each technology in different locations*

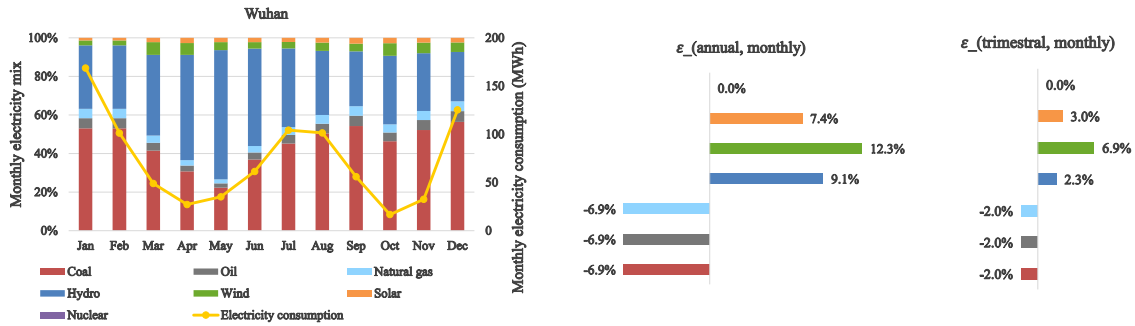
381 Firstly, monthly electricity consumption and electricity mix for each city are displayed in Fig. 9 (left side) to
 382 visualise the link between the two. It is clear that in the northern cities of Harbin and Beijing, electricity consumption
 383 reaches its peak in the winter (around January) and is much lower in the summer due to the low winter temperatures
 384 and high heating demand. In the southern cities of Kunming and Shenzhen, the situation is reversed, with electricity

385 consumption peaking in July. In Wuhan, the electricity consumption curve has two peaks in a year due to the high
 386 demand for both heating and cooling.

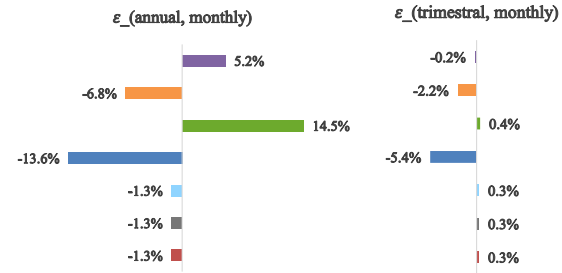
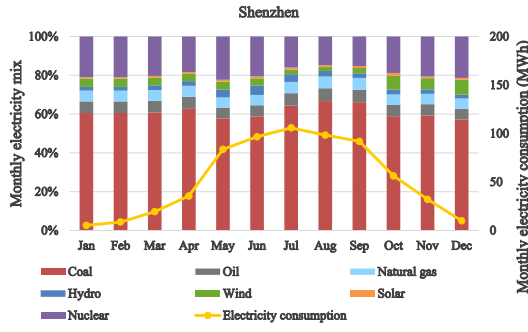
387 An indicator $\varepsilon_{a,b,i}$ that represents the relative gap between the results using two different temporal resolutions for
 388 the technology i , as shown in Eq. (3), is introduced to characterise the gap in the environmental impacts of each
 389 technology when different temporal resolutions of data are employed:

$$\varepsilon_{a,b,i} = \frac{EI_{i,a} - EI_{i,b}}{EI_{i,b}} = \frac{\sum_{t=1}^{ka} (E_t \times R_{i,t} \times I_i) - \sum_{t=1}^{kb} (E_t \times R_{i,t} \times I_i)}{\sum_{t=1}^{kb} (E_t \times R_{i,t} \times I_i)} = \frac{\sum_{t=1}^{ka} (E_t \times R_{i,t}) - \sum_{t=1}^{kb} (E_t \times R_{i,t})}{\sum_{t=1}^{kb} (E_t \times R_{i,t})} \quad (3)$$

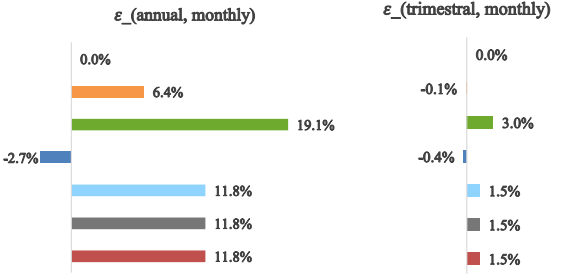
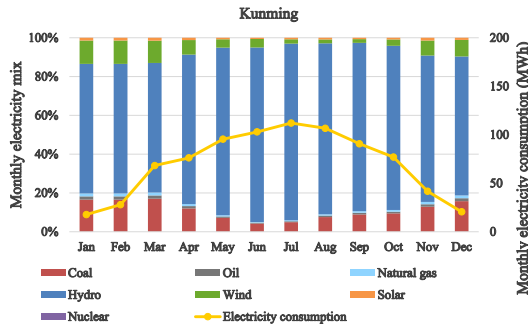
390 where a and b represent two of the three different time resolutions (annual, trimestral, monthly), $EI_{i,a}$ and $EI_{i,b}$
 391 represent environmental impacts of the total power consumption supplied by technology i using the corresponding
 392 time resolution a and b over the 20-year operation stage, ka and kb denote the total number of time steps in the
 393 corresponding time resolution. The corresponding gaps resulting from using annual and trimestral resolution data are
 394 shown on the right side of Fig. 9. These gaps are caused by monthly fluctuations in the electricity consumption curves
 395 and the share of each technology. Since coal, oil, and natural gas were assumed to have fixed proportions in thermal
 396 power generation, the gaps for the three are always the same. It can be envisioned that the use of annual data results in
 397 different levels of underestimation and overestimation of the results for different technologies. In contrast, the use of
 398 trimestral data generally has a smaller impact on the results. This could roughly explain why the use of trimestral
 399 resolution causes almost no discrepancy compared to the results at monthly resolution in Fig. 8.



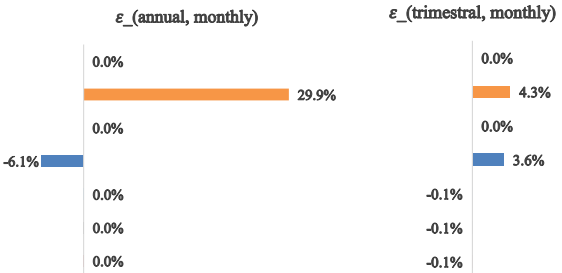
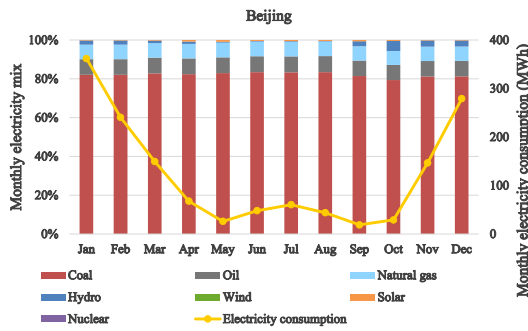
(a)



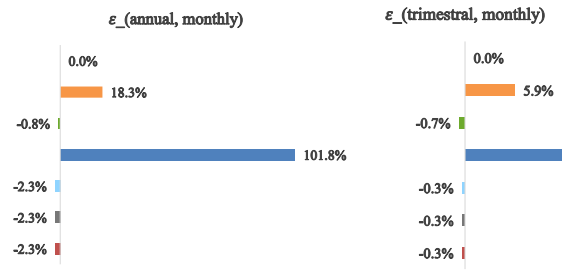
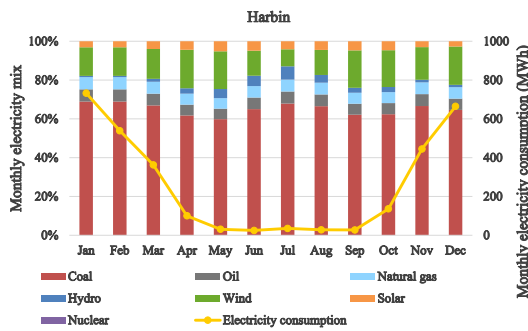
(b)



(c)



(d)



(e)

400 **Fig. 9.** Detailed relationship between electricity consumption and mix in five typical cities (left side) and the corresponding time-
 401 scale gap of each technology (right side).

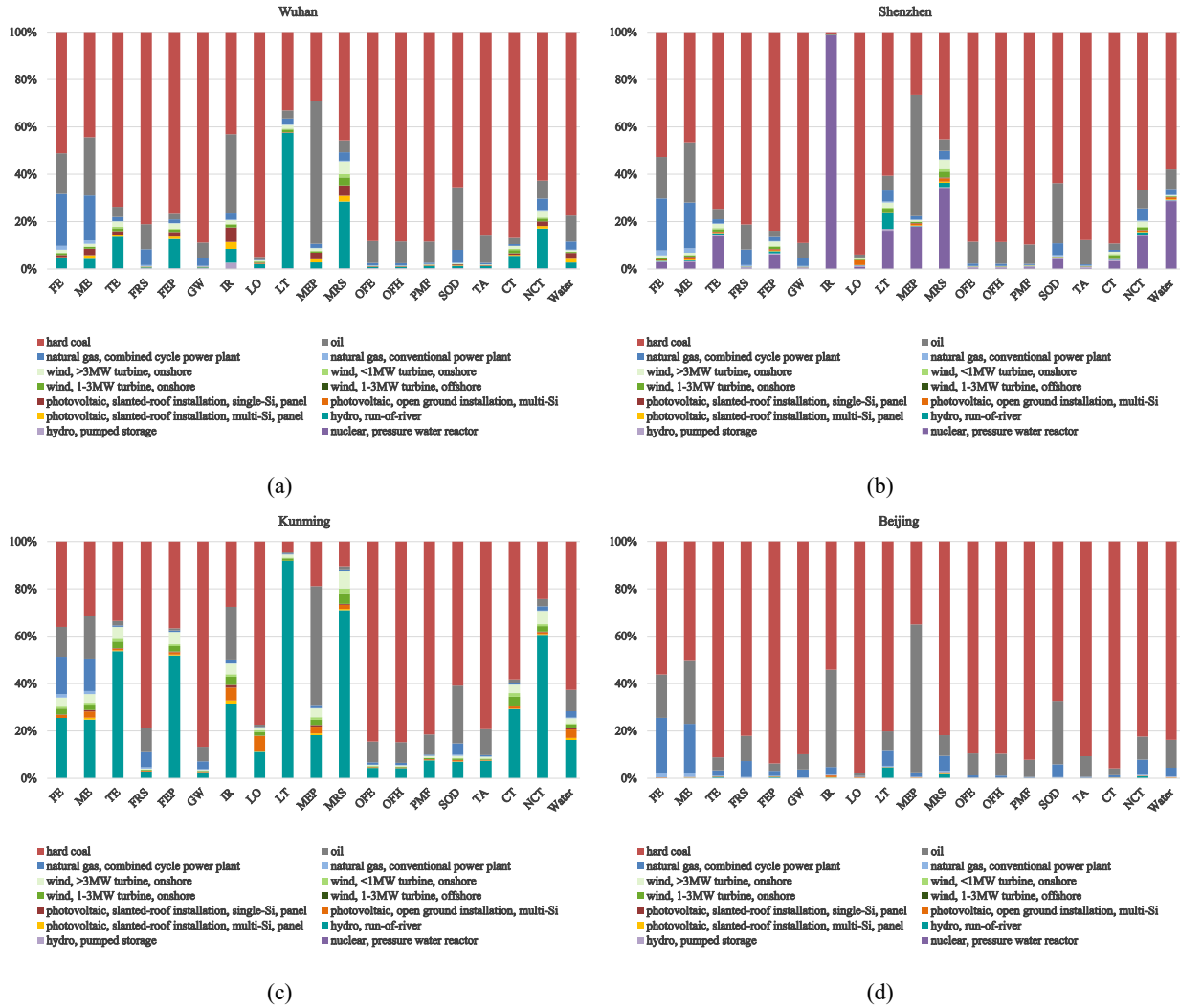
402 3.2.2. Contribution of different technologies in impact results for different categories

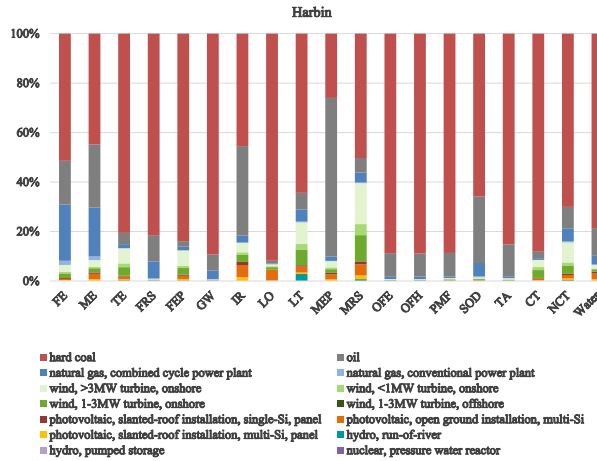
403 Afterwards, taking a deeper look at the share of different technologies in each impact category, as shown in Fig.
404 10, can provide insight into the factors contributing to the variation in category across different time resolutions. In the
405 case of Wuhan (Fig. 10(a)), midpoint categories can be divided into three kinds: thermal-dominated type, thermal-
406 dominated type supplemented by hydro, and hydro-dominated type according to the contribution of different
407 technologies. Most midpoint categories (e.g. FE, ME, FRS, GW, LO, MEP, OFE, OFH, PMF, SOD, TA, CT, and Water)
408 belong to the thermal-dominated type because of a high contribution of hard coal, oil, and natural gas (96 % on average).
409 Since the use of annual resolution data produced a -6.9 % relative gap in the thermal production compared to the use
410 of monthly resolution data (see Fig. 9(a)), the gap of thermal-dominated impacts showed a tendency to be
411 underestimated and the value was close to 6.9 %, as shown in 3.1.2.Fig. 7(b). Midpoint categories such as TE, FEP,
412 IR, MRS, and NCT are grouped to thermal-dominated type supplemented by hydro. The characteristic of this type is
413 that although dominated by thermal energy, their environmental impacts were partially affected by hydropower, which
414 produce a 9.1 % gap under annual resolution. As a result, the underestimation influence caused by thermal production
415 was partially offset and the final gap of this type was lower than that of the thermal-dominated type (-2.8 % on average),
416 as shown in 3.1.2.Fig. 7(b). The hydro-dominated type differs from the other two in that their categories have a
417 relatively high proportion of hydropower (57 % for LT), resulting in the final gap being co-determined by hard coal
418 and hydropower and showing a tendency to be overestimated by 2.9 % with annual resolution data, as shown in
419 3.1.2.Fig. 7(b). The analysis is similar for gaps caused by the use of trimestral data and thus is not repeated here.

420 For Kunming, using annual electricity data induces a relatively high overestimation of 11 %, 19 %, and 6 % for
421 thermal, wind, and solar power, respectively, and a slight underestimation of 2.7 % for hydropower (Fig. 9(c)). Hence
422 the final gap depends on the share of hydropower generation technologies in each category of environmental impacts
423 (Fig. 10(c)). When the share of hydropower technologies is low, such as FRS, GW, and LO, etc., the relative gap is
424 large, and the value varies between 6 % and 19 % depending on the share of other technologies. When the share of
425 hydropower technologies is high, such as LT, MRS, and NCT, etc., the underestimation effect from hydropower is
426 offset by the overestimation effect from other technologies, and thus the relative gap is low, as shown in Fig. 8(b).

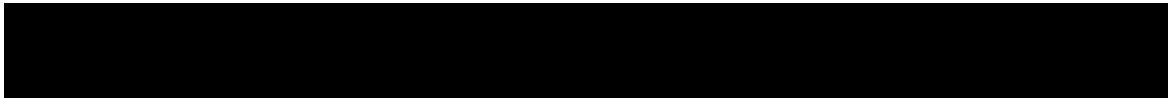
427 The trend for Shenzhen is similar as for Wuhan, with most categories dominated by thermal energy (Fig. 10(b)).
428 But minimal relative gaps in the thermal energy (Fig. 9(b)) led to small relative gaps for most categories, except for
429 IR, which derives 98.8% of its impact from nuclear energy and thus presented a relative gap of 5.1 %, as shown in Fig.

430 8(a). The situation in the Beijing context is quite simple (Fig. 10(d)), where all midpoint categories were dominated
 431 by thermal energy. Since the monthly mix of thermal energy remained almost unchanged (Fig. 9(d)), the relative gap
 432 was close to zero when using different temporal resolutions, as shown in Fig. 8(c). In the case of Harbin, only solar
 433 and hydropower have significant monthly variations in the corresponding electricity mix (Fig. 9(e)), but the
 434 contribution of these production techniques to all midpoint categories is too small (see Fig. 10(e)) to lead to a noticeable
 435 gap, as shown in Fig. 8(d).





(e)



436 **Fig. 10.** Contribution of different technologies in the midpoint categories for five typical cities.

437 To conclude, for each category, the relative gap between the results using two different temporal resolutions is
 438 determined by weighting the gap for each technology with its contribution ratio. The contribution ratio of a technology
 439 i is defined by the life cycle impact of the technology under the category I_i and its total consumption C_i , as described
 440 in Eq. (2), while the relative gap is due to the different temporal resolutions used to calculate the energy consumption
 441 of each technology $\varepsilon_{a,b}$, as explained in Eq. (3). In other words, if one category corresponds almost entirely to one
 442 technology, then its final gap is influenced by the gap of that technology.

443 *3.3. LCIA results of reversible GCHP systems supported by DOEIA method*

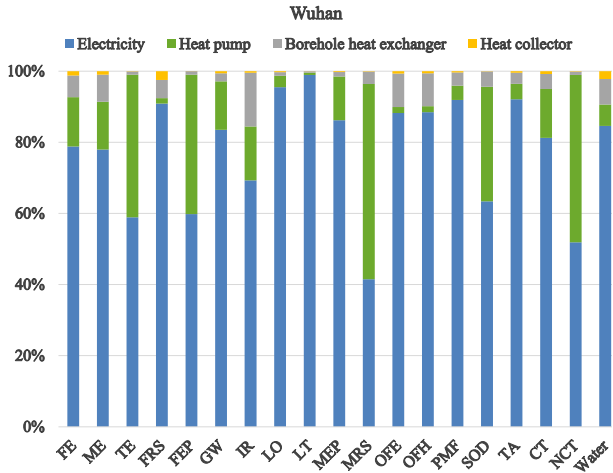
444 LCA results regarding manufacturing, installation, transportation, and end-of-life phases were calculated using
 445 Brightway2/Activity-browser (Steubing et al., 2020) and data collected from the Ecoinvent v3.4 database (Wernet et
 446 al., 2016). Environmental impacts related to electricity consumption during the operation stage were then included to
 447 get the total life cycle impacts. It should be noted that the technical life span is assumed 100 years for ground heat
 448 exchanger and heat collector (Violante et al., 2022), which corresponds to five operational life cycles of the heat pump.
 449 Therefore, in this study, the environmental impact of the ground heat exchanger and heat collector was correspondingly
 450 equated to one-fifth of the total for a 20-year study period.

451 *3.3.1. Relative contributions of the system in all indicators*

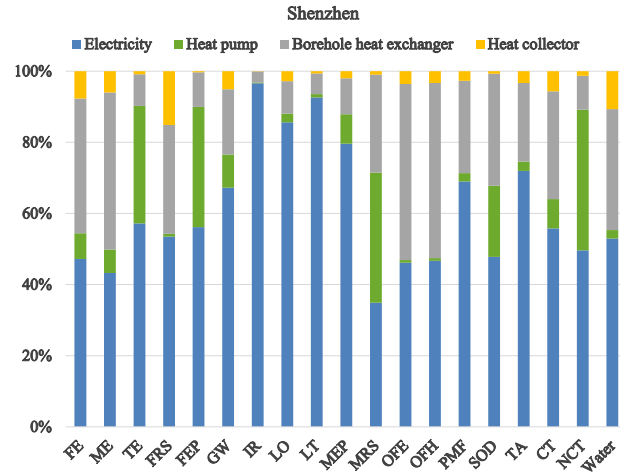
452 Fig. 11 shows the relative contributions of the four technological elements (heat pump, ground heat exchanger, heat
453 collector, and electricity) to the total scores within each category for the five cities. The absolute values of each element
454 at midpoint levels are displayed in Table A7. It can be observed that, in general, electricity has a fairly high contribution
455 ratio in most categories of most cases. To be specific, electricity has a contribution ratio of over 60 % in almost all
456 categories in the Wuhan, Harbin, and Beijing cases, with over 80 % in more than half of the categories in the Wuhan
457 and Beijing cases. Taking Wuhan as an example, the contribution of electricity in MRS, NCT and TE is relatively low
458 at 41 %, 52 % and 59 % respectively. Among them, 55 %, 47 % and 40 % of the impacts come from heat pumps,
459 respectively, which is primarily caused by the copper production in the heat pump system. In addition, 39 % of the
460 FEP impacts and 32 % of the SOD impacts are from the heat pumps, which are mainly related to the treatment of
461 sulfidic tailings in the copper mine operation and the production of refrigerant R410a, respectively.

462 Compared to the Wuhan case, the 20-year total electricity consumption to maintain thermal comfort of building
463 occupants has increased by 67 % and 261 % in the Beijing and Harbin cases, where the demand for heating is
464 substantial. Correspondingly, the amount of GHEs required is significantly higher, 4 and 34 times more than in the
465 Wuhan case, respectively, as shown in Table A4 of Appendix. Since the increase in GHE is more significant than in
466 electricity, it is reflected in the final environmental impact share, which shows that the proportion of GHEs in each
467 category increases to some extent in both the Beijing and Harbin cases, with a higher increase in the Harbin case.

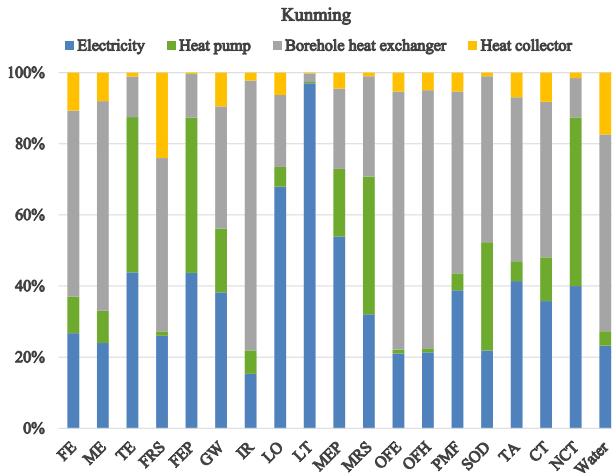
468 The Kunming and Shenzhen are similar in that the electricity consumption as well as heat pump demand for both
469 are close to the Wuhan, but the demand for GHE is higher than the Wuhan because of a higher imbalance between the
470 cooling and heating loads, as shown in Table A3 of Appendix. This high level of imbalance means that the heat
471 accumulated underground over a year is high, so a large amount of GHEs need to be arranged to deal with this heat in
472 order to maintain the outlet temperature of GHEs within a reasonable range to ensure proper operation of the HP.
473 However, due to the large portion of clean energy sources such as hydro and wind in its electricity mix, Kunming's
474 electricity consumption contributes less to the environmental impacts than the other cities that are dominated by
475 thermal power. Therefore, the share of electricity in the Kunming case is significantly lower in almost all categories.
476 It is also notable that Shenzhen, with a certain percentage of nuclear power in its electricity mix, shows an increase
477 rather than a decrease in the share of electricity in the category IR (Ionizing Radiation) compared to the other cities.



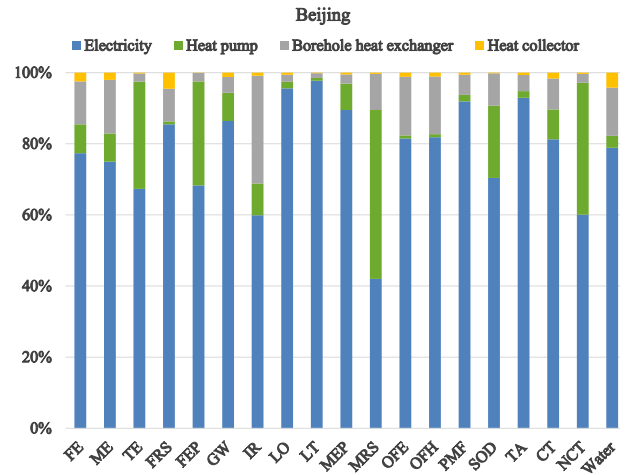
(a)



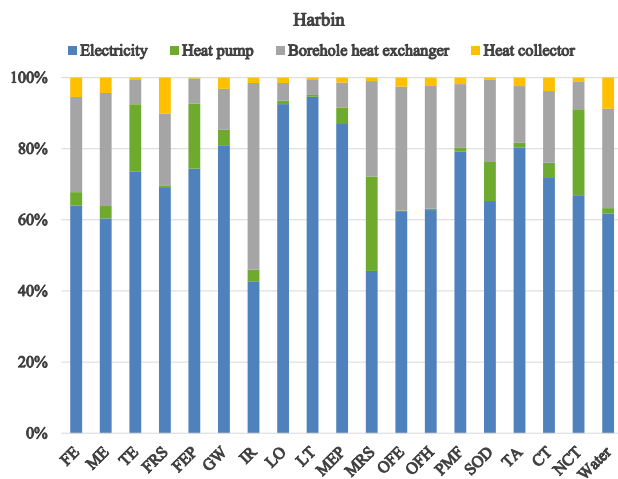
(b)



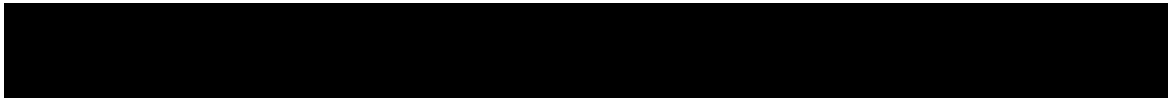
(c)



(d)



(e)



478 **Fig. 11.** Relative contributions of each technological element to all midpoint categories for the five cities.

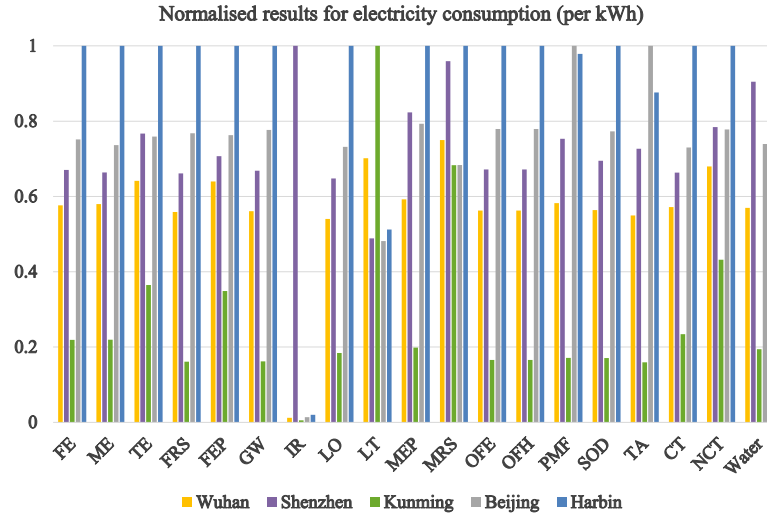
479 *3.3.2. Normalised comparison between locations*

480 For a better comparison of the environmental impacts between the different locations, the results were divided by
 481 the total electricity consumption and then normalised by the maximum value of each category among all five cases, as
 482 displayed in Fig. 12. The total electricity consumption of the five cities is shown in Table 2. It can be found that for
 483 the environmental impact results per unit of electricity consumed, Harbin has the maximum value in 15 of the 19
 484 categories, while Kunming has minimum values for all 18 categories except LT (Land Transformation). This is
 485 attributed to the high ratio of thermal energy in Harbin's electricity mix, as well as the fact that the environmental
 486 impact of its thermal power technology per unit of electricity generated is higher than that of the other two thermal
 487 dominant cities (i.e., Shenzhen and Beijing) in almost all categories (see Table A8). Kunming, on the other hand, has
 488 the cleanest electricity mix, mainly hydropower, and its environmental impacts per kWh of electricity consumed are
 489 generally the smallest with the only exception being the LT (Land Transformation) category, which, due to having a
 490 large number of run-of-river power plants, has the largest impacts across all cases. Furthermore, Shenzhen
 491 distinguishes itself in the category IR (Ionizing Radiation) because it is the only case with a nuclear share of about 20 %
 492 compared to the other four. After combining the environmental impacts of the electricity consumption with impacts of
 493 other stages of GCHP system, Harbin retains its peak position in most categories due to the highest demand for GCHP
 494 system in terms of heat pump, ground heat exchanger, and heat collector. For the same reason, Kunming and Shenzhen
 495 show an increasing trend in the normalised impacts under each category. Wuhan and Beijing, which benefit from a
 496 relatively small number of ground heat exchangers, have slightly lower normalised impact results in most categories.
 497 Overall, Wuhan and especially Kunming show better environmental performance, both in terms of operating energy
 498 consumption and the whole GCHP system, which reinforces the importance of a cleaner energy mix.

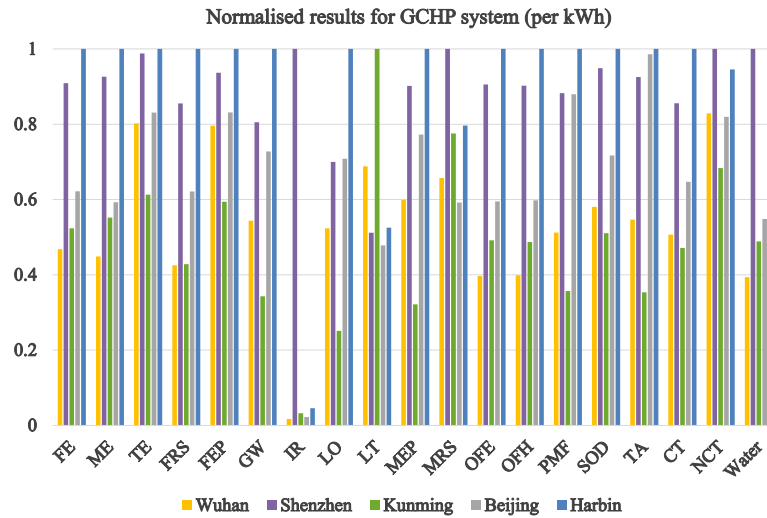
499 **Table 2** Detailed electricity consumption in five locations.

Total electricity consumption in 20 years		Wuhan	Shenzhen	Kunming	Beijing	Harbin
Heating season	MWh	8,401.34	277.03	0	24,642.57	60,568.10
Cooling season	MWh	8,947.30	13,563.25	18,871.26	4,414.02	2,027.18
Total	MWh	17,348.64	13,840.28	18,871.26	29,056.59	62,595.28

500



(a)



(b)



501 **Fig. 12.** Normalised results for (a) electricity consumption and (b) GCHP system in the five cases.

502 **4. Discussions**

503 The results of this work can be divided into two main aspects: one is the results of the DOEIA methodology and
 504 the precision analyses and assessment of influencing factors involved (Sections 3.1 and 3.2); the other is the LCA
 505 results of the GCHP system in different climate zones based on the DOEIA method (Section 3.3). Several outlooks and
 506 reflections on this study are listed below from each of these two aspects. For the first aspect, since the DOEIA

507 methodology is generalizable to other energy systems, the focus is on the electricity mix and energy consumption,
508 which play a key role in the accuracy of the DOEIA results.

- 509 • The difference caused by considering the dynamic energy mix is already visible in our case studies, with an
510 average underestimation of 5.6 % for Wuhan and an average overestimation of 8.1 % for Kunming and is expected
511 to grow further in other scenarios. On one hand, temporal sensitivity of operational environmental impacts could
512 be larger in other locations with stronger variations of local electricity mix and system energy consumption. These
513 areas should therefore be particularly aware of the risks of using traditional static methods for environmental
514 impact assessment. On the other hand, given the global energy transition, the share and importance of renewable
515 energies will increase in the future. As renewable energy sources such as photovoltaic and wind power have high
516 seasonal, monthly, and even daily fluctuations in power generation, it is undoubtedly more critical to consider the
517 dynamic energy mix in order to accurately assess the environmental impacts of energy systems.
- 518 • This research assumed that the annual electricity mix at different locations remains constant during the operational
519 phase of the system, as do the meteorological condition data used in modelling dynamic building energy
520 consumption. In reality, however, global climate change may on the one hand reshape the heating and cooling load
521 ratios of buildings, e.g., warmer temperatures may cut cooling loads and increase heating loads in buildings.
522 Depending on the climate zone of the building in which the system is applied, this may increase the volatility of
523 dynamic electricity consumption. On the other hand, climate change might also facilitate the evolution of the
524 electricity mix in conjunction with local policies, with the share of renewable energy sources, such as photovoltaics,
525 continuing to increase. Likewise, technologies employed to meet heating and cooling needs will evolve towards
526 integrating more renewable energy sources. Therefore, the assumption in this work is likely to cause an
527 underestimation of the operational environmental impact results, so it would be an interesting perspective to
528 perform prospective analysis in the future.
- 529 • Due to data unavailability, this work did not evaluate the dynamic results at a higher temporal resolution (e.g.,
530 hourly). Comparative studies with higher temporal resolutions can be conducted in countries where such data is
531 available, and it might reveal larger disparities in operational environmental impacts between different impact
532 categories. Meanwhile, investigations on an hour-by-hour basis could help to move towards optimal control and
533 peak-shifting. Besides, it would be useful to elaborate on such data over the whole century, corresponding to
534 common buildings' life span.

535 • The dataset Ecoinvent v3.4 forms the basis of our life cycle inventory. Therefore, updates introduced in the latest
536 version, v3.10, are not included in this study, which could be improved in the future. Additionally, some of the
537 statistics in Ecoinvent dataset are based on earlier years of data. For instance, life cycle inventories corresponding
538 to 1 kWh of electricity produced by different technologies at the high voltage level (above 24 kV) are based on
539 grid-connected power plants in various provinces of China in 2012. Although no newer dataset is currently
540 available to researchers, improving these inventories with more recent data could further enhance the reliability
541 of this study.

542 For the second aspect, the focus is on the characteristics of the GCHP system itself.

543 • Unbalanced building thermal loads or single operation mode (heating only/cooling only) could cause performance
544 degradation of the GCHP system over long periods of operation, thus creating a potential gap in the impact
545 assessment of operational energy consumption. This performance drop can be mitigated to some extent through
546 design optimisation (Kurevija et al., 2012; Qian and Wang, 2014), operational strategies (Dai et al., 2015; Shang
547 et al., 2014), and hybrid technologies such as cooling tower (Gong et al., 2018), thermal storage technologies
548 (Zhai et al., 2011), and ground source absorption heat pumps (Wu et al., 2015), among others. Thus for GCHP
549 systems, the influence of long-term performance degradation on the environmental impact of the operation phase
550 can also be somewhat alleviated, but this will certainly be at the expense of the environmental impacts of other
551 phases (e.g., manufacturing, installation, and maintenance of other auxiliary systems, more land occupation for
552 larger GHE configurations, etc.), and therefore needs to be considered holistically and analysed on a case-by-case
553 basis.

554 • The appropriate application of GCHPs can reduce electricity consumption during the operational phase of
555 buildings compared to conventional cooling and heating technologies such as air-cooled air conditioners and
556 boilers, providing a solution to reduce peak energy demand through renewable energy sources and facilitating the
557 energy transition. Such a question would require studying transition scenarios on a larger scale. In terms of cleaner
558 and sustainable production, there are still several potential improvements that could further enhance the
559 environmental performance of GCHP systems. One of the recommended approaches is to apply renewable energy
560 as a source of electricity or to couple GCHP with renewable technologies (e.g. hybrid geothermal-photovoltaic
561 system (Violante et al., 2022)) to reduce the demand for electricity in the grid, which has great potential
562 considering the dominance of electricity in the impact category results (over 60 % in almost all categories in the

563 Wuhan, Harbin, and Beijing cases, and over 80 % in more than half of the categories in the Wuhan and Beijing
564 cases). Another recommendation is to replace the polyethylene pipes with steel pipes for ground heat exchangers
565 (Ren et al., 2018). This has been proven to reduce global warming and human health impacts by approximately
566 43.91 % and 43.15 %, respectively, as steel pipes could effectively reduce electricity consumption during the
567 operational phase of the system (Zhai et al., 2022).

- 568 • The assumptions for the end-of-life phase in this work are based on the previous study by Violante et al. (2022),
569 where only the end-of-life phase of the heat pump was considered because the technical lifetime of the vertical
570 GHEs and heat collectors (100 years) far exceeds that of the heat pump (20 years in our study). In addition,
571 considering that many previous studies have shown that the end-of-life phase can be excluded from the study
572 scope due to its limited significance (L. Luo et al., 2023; Pieskä et al., 2023), the impact of the end-of-life phase
573 of the GHE after proportional reduction of the technical life will be even smaller, so its exclusion is considered
574 acceptable in this study. However, attention still needs to be paid to the potential environmental impacts of vertical
575 GHEs and cement filling.

576 **5. Conclusions**

577 In this paper, a reversible GCHP model was coupled to the dynamic building energy simulation tool COMFIE to
578 generate dynamic energy loads over the life span of the system. Benefiting from monthly electricity mix data, a
579 dynamic LCA methodology was applied to improve, compared to a static LCA, the precision of results by considering
580 dynamic performance variation of the reversible GCHP system. Results demonstrate that in the case of Wuhan, when
581 the long-term performance degradation is not considered, the use of an annual average mix and electricity consumption
582 instead of monthly data can lead to an average underestimation of 9.6 % for all midpoint categories, with the largest
583 underestimation being 11.5 % for Global Warming. Moreover, investigations on implications of spatial variations on
584 the environmental impact variation of operational energy consumption indicate that the global impact variation can be
585 evaluated in terms of the contribution of the different technologies in the electricity production mix. Therefore, if an
586 impact category is largely influenced by one technology, then the variation of this impact indicator (in terms of temporal
587 resolution or location) is significantly affected by the variation of the share of this technology in the electricity
588 production mix (e.g. thermal-dominated type impact categories in Wuhan case). Nevertheless, if one impact category
589 is jointly influenced by multiple technologies with significant variations in the mix, their cumulative impact may offset

590 each other, resulting in a negligible final variation of the corresponding impact indicator (e.g. thermal-dominated type
591 supplemented by hydro impact categories in Wuhan case). At last, the LCIA results of the reversible GCHP system in
592 different locations also underline the necessity of a cleaner energy mix to achieve a net zero emissions future. This
593 study can provide a reference for future LCA studies of other energy systems according to their use and local electricity
594 mix, and potentially guide them in evaluating the necessity of considering higher resolution in their research. Given
595 the shaping of building dynamic demand by climate change and the development of energy-efficient buildings, as well
596 as the evolution of the power mix prompted by policies and regulations, assuming the same annual dynamic electricity
597 mix and meteorological conditions for the time horizon of this study may lead to an overestimation of the overall
598 environmental impacts of the GCHP system. Further work can be initiated by integrating prospective climate and
599 electricity mix data into long-term dynamic LCA studies. Additionally, higher hourly resolution studies may reveal a
600 wider gap in operational environmental impacts across different impact categories, and this should be further
601 investigated in the future when data becomes available to help move towards optimal control and peak-shifting.

602 **Declaration of Competing Interest**

603 The authors declare that they have no known competing financial interests or personal relationships that could have
604 appeared to influence the work reported in this paper.

605 **Acknowledgement**

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

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