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Life cycle assessment of building reversible ground-coupled heat pump systems supported by dynamic electricity mix data

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Abstract

Ground-coupled heat pump (GCHP) systems provide indoor comfort but contribute to greenhouse gas emissions and other impacts on human health, ecosystems, and resources. Life cycle assessment (LCA) methodology has been employed to evaluate the environmental impacts associated with GCHP systems, with an application in China. Previous studies have disregarded the effect of building cooling and heating load imbalances on the long-term operating performance of the system, relying on static COPs and annual average data to obtain the environmental impacts. In this paper, an LCA method based on dynamic electricity mix and energy consumption data was used to assess the long-term operational environmental impacts of a reversible GCHP system. Results indicated that using annual temporal resolution and neglecting long-term impacts lead to an average underestimation of 6.5 % for all indicators, with an underestimation of 9.2 % for Eutrophication Potential.

Highlights/Key innovations

- A life cycle assessment methodology of GCHP systems is developed using dynamic electricity mix and consumption data to improve precision.
- A reversible GCHP model is coupled with a building energy simulation tool to obtain the dynamic energy consumption.
- The influence of using three different temporal resolutions on the accuracy of the LCA results of GCHP systems is compared.
- The impact of performance degradation due to seasonal building- load imbalance on the accuracy of the LCA results is evaluated.

Practical implications

This study highlights the importance of considering long-term system performance variation and improving the temporal resolution of energy consumption for life cycle assessment, providing a more accurate assessment of heat pump systems environmental impacts.

Introduction

China is currently undergoing rapid urbanisation and experiencing an increase in living standards (Chang et al., 2017). The total energy consumption of the building sector (including material production, construction, and operation) represents 46.5 % of the total national energy

consumption, and the total carbon emission of the whole building process accounts for 51.3 % of the national carbon emission (CABEE, 2020). As urbanisation accelerates, the building sector is expected to increase its energy consumption and therefore has great potential for energy conservation and environmental sustainability in China (Lin and Liu, 2015).

Heating and cooling systems have a large share up to 40 % of building total energy consumption in China (González-Torres et al., 2022). As one of the most promising technologies to realize energy conservation and emission reduction, GCHP systems benefit from reliable energy sources, stable operating conditions, and easy maintenance compared to other heating and cooling systems such as furnaces and air source heat pump (Chang et al., 2017; Han et al., 2017). Despite the indoor comfort it provides, ground-coupled heat pump systems contribute to greenhouse gases emissions and other impacts on human health, ecosystems, and resources.

LCA is currently recognised as one of the most comprehensive and robust approaches to evaluate environmental impacts of products or services. Some studies have employed LCA to evaluate the environmental impacts associated with GCHP systems, and applications were performed in China. It was shown that the electricity supply in the operation stage usually dominates environmental impacts (Saner et al., 2010), and the reduction in electricity generation processes plays a crucial role in mitigating the environmental impact across all the determined midpoint and endpoint categories (Zhai et al., 2022). As a result, in light of the data-intensive nature of LCA, electricity generation, particularly during the operation stage, should be prioritised to refine the accuracy of LCA results. Previous studies, however, have relied on static COP (Coefficient of Performance) and annual average electricity mix data to obtain environmental impacts (Aresti et al., 2021; Koroneos and Nanaki, 2017; Saner et al., 2010; Violante et al., 2022; Zhai et al., 2022; Zhang et al., 2022). In addition, the degradation of the long-term performance of GCHP system due to the imbalance of the building cooling and heating loads was not taken into account, and annual electricity consumption was assumed to remain the same during the lifespan. All these low-resolution estimates might lead to a loss of precision in the ultimate outcomes.

In recent years, a growing number of researchers have become aware of the influence dynamic data can have on the precision of LCA analysis. Roux et al. (2016) assessed the environmental impacts of an energy-efficient house by considering the temporal variation of electricity production. The study showed that the use of an annual average mix can cause underestimation of potential impacts compared to hourly blended data results, with abiotic depletion potential being underestimated by up to 39 % and global warming potential by up to 36 %. Subsequently, an electricity system model was developed to apply dynamic and marginal approaches in LCA (Roux et al., 2017). The electricity supply was simulated on an hourly basis and the proposed reference year was expected to take into account the impact of economic and meteorological hazards of real historical years. However, according to the IEA real-time electricity tracker (Figure 1), the historical and real-time hourly and daily data are not accessible in all countries. This hourly resolution is currently not available for China. Power supply changes with the months and seasons (Beloin-Saint-Pierre et al., 2017), and so do the impacts of GCHP systems. Therefore, it is valuable to evaluate the environmental impacts of GCHP systems accounting for temporal variation.

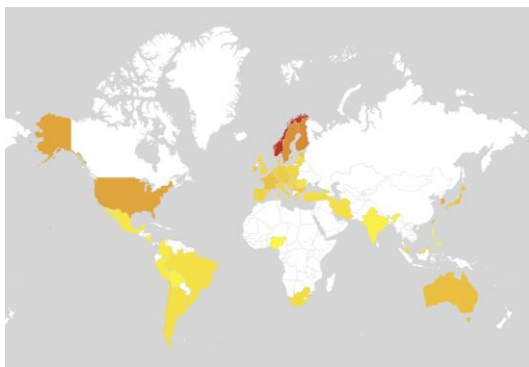


Figure 1: Real-time electricity map (IEA).

In this paper, a reversible GCHP model is coupled to a building energy simulation tool to generate dynamic heating and cooling loads. Timesteps of one month, one trimester, and one year were chosen to evaluate the effect of different time resolutions on the accuracy of LCA results.

Methods

Functional unit and system boundary

In this study, a reversible ground-coupled heat pump system, as the most commonly employed ground source heat pump type in China (Zhou et al., 2016), was selected to meet the heating and cooling needs of a small residential block consisting of 4 residential buildings in Wuhan, China. The life span of the heat pump was assumed to be 20 years (Greening and Azapagic, 2012). The functional unit was therefore defined as providing heating and cooling that maintains the indoor temperature of the building between 18 °C and 26 °C during 20-years.

The system boundary of the reversible GCHP system includes manufacturing, installation, and operation stages, as illustrated in Figure 2. Transportation and End-of-life stages were excluded due to negligible impacts and data limitations (Bartolozzi et al., 2017; Violante et al., 2022; Zhang et al., 2022). Terminal units were not modelled because they are not specific to GCHP systems. When evaluating the energy consumption of the building, a radiant floor system was considered and distribution losses were neglected (i.e. 100 % efficiency).

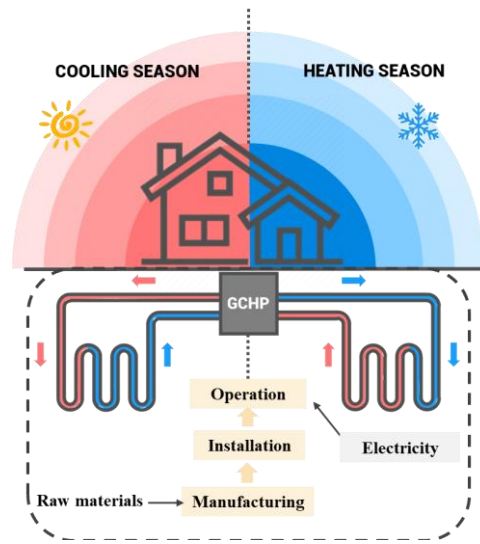


Figure 2: System boundary.

Dynamic environmental impact assessment method

The environmental impact assessment method in this study can be divided into two main parts: one focusing on the impact of dynamic electricity consumption during the operational stage and one focusing on the impact of the manufacturing and installation part of the system. Unlike current LCA studies of GCHP system, the dynamic electricity consumption part takes into account the interaction between the building and the GCHP system, including the long-term performance fluctuation caused by building seasonal imbalance. The process of evaluating environmental impacts based on dynamic electricity mix data is displayed in Figure 3.

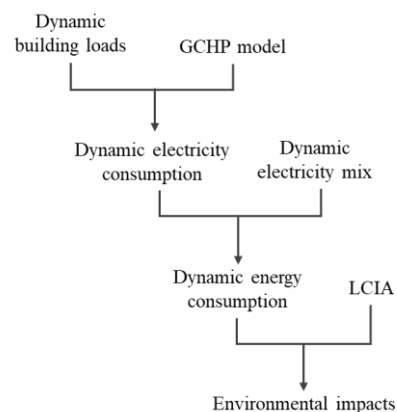


Figure 3: Environmental impact assessment method based on dynamic electricity mix data.

A residential building model located in Wuhan, Hubei is created in the building simulation software COMFIE (Thiers and Peuportier, 2012) to generate dynamic building loads. A reversible ground-coupled heat pump (GCHP) model, consisting of a parameter estimation-based steady state semiempirical model of water-to-water heat pump with rotary compressor (Filliard, 2009; Jin and Spitler, 2003) and a global model of large-scale boreholes heat exchangers (Pei et al., 2022b), is then integrated into COMFIE so that building energy loads can be transformed to dynamic electricity consumption on the basis of real-time energy efficiency of the system at each timestep. The heat pump system can be described with few parameters regarding compressor, heat exchangers, and expansion valve, as listed in Table 2. Following this, the total energy consumption can be calculated based on the dynamic electricity mix in Wuhan. Finally, the environmental impacts can be derived from the life cycle impacts of different sources of electricity.

Table 2: Parameter of the heat pump model in the case study.

Component	Parameter	Unit	Value
Compressor	Refrigerant volume flow rate	m ³ /s	0.4167
	Compressor leakage rate	m ³ .Pa/s	0.0063
	'Built-in' volume ratio	-	2.99
	Polytropic coefficient	-	1.2012
Heat exchanger	Electro-mechanical power losses	kW	0.333
	Electro-mechanical efficiency	-	0.983
	Evaporator effectiveness	-	0.83
Expansion valve	Condenser effectiveness	-	0.99
	Overheat temperature at the outlet of the evaporator	°C	7

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

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

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

where C_f is the characterisation factor matrix, LCI_i is the life cycle inventory of one kWh produced by technology "i", $LCI_{network,i}$ is the life cycle inventory of electricity network infrastructure per kWh supplied in Hubei

province for technology "i", 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 (Pei et al., 2022a).

Twelve indicators are chosen to evaluate the environmental impacts of the GCHP system according to equation (1). The selection of these indicators is based on their ability to encompass the three primary domains of interest in LCA: human health, ecosystem quality, and resources (Pei et al., 2022a; Peuportier et al., 2013), as shown in Table 2. The main impact categories that cause harm to ecosystem quality and human health (climate change, acidification, photo-oxidant formation, eutrophication, and land use) are evaluated by five midpoint indicators. Another midpoint indicator is the abiotic and fossil resources depletion potential. Two endpoint indicators are evaluated: the total damage to ecosystems in PDF.m².year (Potentially Disappeared Fraction of species over a certain territory and during a certain time) and total damage to human health in DALYs (Disability Adjusted Life Years). In addition, abovementioned environmental indicators are complemented by four flow indicators: energy, water consumption, waste, and radioactive waste (Pei et al., 2022a).

Table 3: Environmental impact indicators.

Impact indicators	Unit	Method
Global Warming Potential (100) (GWP)	kg CO ₂ eq.	IPCC 2013: climate change GWP 100a
Acidification Potential (AP)	kg SO ₂ eq.	IMPACTWorld+ 1.28: freshwater and terrestrial acidification
Photochemical Oxidant Formation (POP)	kg C ₂ H ₄ eq.	CML 2016
Eutrophication Potential (EP)	kg PO ₄ eq.	IMPACTWorld+ 1.28: freshwater eutrophication
Land occupation (Land)	m ² .yr	Ecological footprint
Abiotic Depletion Potential (ADP)	kg Sb eq.	CML 2016: elements (ultimate reserves)
Cumulative Energy Demand (CED)	MJ eq.	CED: fossils and non-renewables
Water consumption (Water)	l	EQUER
Waste	kg	EQUER
Radioactive Waste (Rad)	m ³	EQUER
Damage caused to ecosystems (Bio)	PDF.m ² .yr	IMPACTWorld+ 1.46: total damage, long term
Damage to human health (DALY)	DALY	IMPACTWorld+ 1.46: total damage, long term

Data sources

Figure 4 and Figure 5 show the monthly electricity mix data in Wuhan province and China separately (National Bureau of Statistics, 2022). It can be seen that even though both are thermal-dominated electricity generation, there are still noticeable differences between the two. Compared to the national electricity mix, Wuhan's power grid exhibits a larger share of hydropower and less nuclear power. In this study, monthly electricity mix between November 2021 and October 2022 was selected and assumed to be identical in the operation stage of the GCHP system.

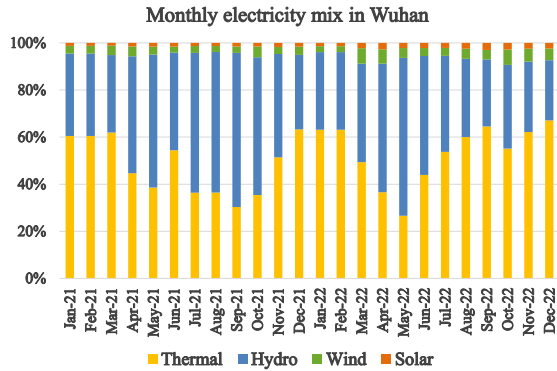


Figure 4: Monthly electricity mix in Wuhan.

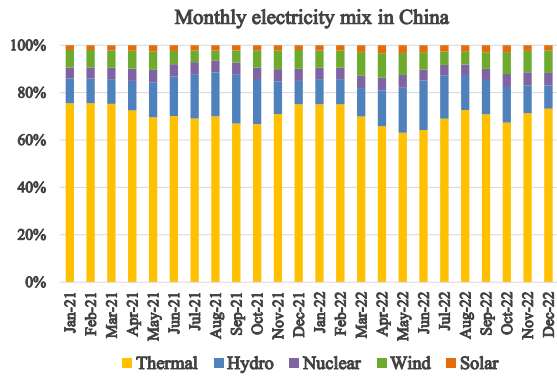


Figure 5: Monthly electricity mix in China.

When it comes to electricity production, only photovoltaic systems are considered to release power at low voltage, all other technologies are recognized for producing electricity at high voltage (above 24 kV). The share of coal, oil, and gas in thermal power generation in Wuhan is assumed to be equal to the national share (National Bureau of Statistics, 2022). The proportion of different technologies in each energy source is assumed to be identical during the system operation stage. Detailed technologies are listed in Table 4.

Table 4: Detailed technologies in Wuhan.

Technology	Detailed technology description
Coal	Centralised power plant from coal
Natural gas	Conventional power plant (6.9 %) and combined cycle power plant (93.1 %)
Oil	Oil power plant
Hydro	Run-of-river (99.6 %) and pumped storage (0.4 %)
Wind	Onshore turbine <1 MW (15.6 %), 1-3 MW

	(45.8 %), >3 MW (38.6 %)
Solar	Single-Si panel (65 %), multi-Si panel (35 %)

The hourly heating and cooling loads can be obtained through the dynamic building energy simulation (DBES) software COMFIE. The weather file in Wuhan was downloaded from EnergyPlus website (EnergyPlus, n.d.). Manufacturing, installation, and operation of the vertical borehole heat exchangers, the heat collector, and GCHP was considered in this study. Data used in the manufacturing and installation stage of GCHP system was acquired from different sources (Greening and Azapagic, 2012; Saner et al., 2010; Violante et al., 2022), using Ecoinvent datasets for related processes. The data was then contextualised based on the electricity mix in China and complemented with calculated energy consumption. The heat collector for the GCHP system includes both vertical and horizontal high-density polyethylene (HDPE) pipes that connect the wellhead to the heat pump. The vertical pipes measure approximately 31 cm each and have a total length of 838 m, consisting of 2704 pipes from the 676 boreholes. These pipes are insulated with low-density polyethylene (LDPE). Additionally, the horizontal manifold is comprised of 230 m of HDPE pipe placing in a 1 m deep trench, which connects each double-U pipe from every borehole. Overall, the system has a total pipe length of 1068 m, which includes 230 m of HDPE horizontal and 838 m of HDPE vertical pipes.

Results

Dynamic energy simulation of reversible GCHP

The DBES tool COMFIE was used to evaluate hourly heating and cooling loads of the studied residential buildings according to the building envelope, HVAC equipment, local meteorological conditions, occupancy, and internal gains. Results are displayed in Figure 6. The peak heating and cooling power are 2627 kW and 2096 kW, respectively. The annual heating and cooling loads are 2577 MWh and 2798 MWh, respectively. The annual heating and cooling loads per unit area are 51 kWh/m² and 55 kWh/m², respectively.

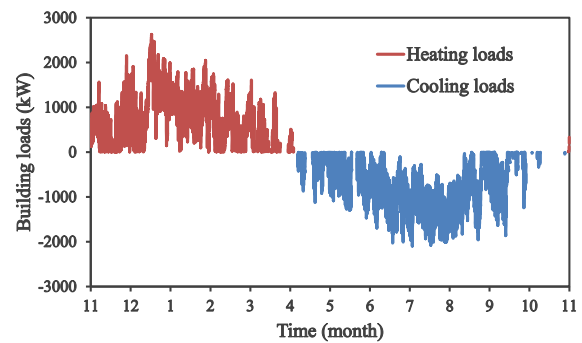


Figure 6: Hourly building heating and cooling loads over a year.

Accordingly, a square field of 26×26 vertical boreholes (133 m deep) was designed to provide heating and cooling needs for studied buildings. A detailed schema of the geometry of buried piping circuit is shown in Figure 7. The sizing design of borehole refers to the

actual air-conditioning solution of the project case, taking into account the cost, available land area, and, most importantly, the building cooling and heating loads, etc (Vkhvacr, n.d.). Relevant parameters were then included in a reversible GCHP model combining the finite line source model, the 2D heat equation and a three-points method (Pei et al., 2022b). This model was integrated in COMFIE to consider the long-term interactions between building, ground and GCHP system. The outlet temperature of the ground heat exchanger (GHE) in a multi-year simulation is displayed in Figure 8. To better observe the multi-year evolution of system performance in different modes, the simulation started at the beginning of the heating season. When running the GCHP system in “heating and cooling” mode, the absolute temperature drift of GHE was mitigated compared to “heating only” and “cooling only” mode since the cooling loads could partially balance the heating loads.

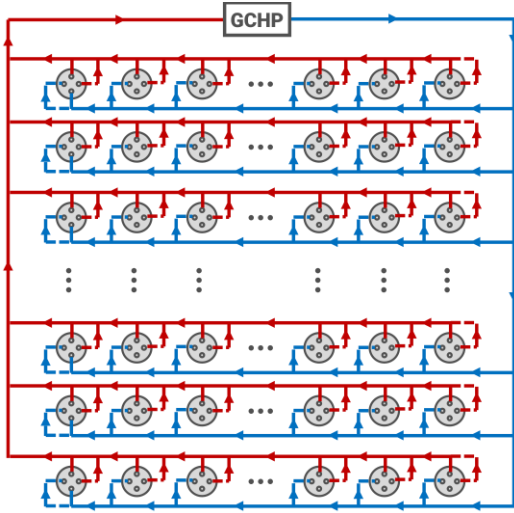


Figure 7: Schematic diagram of the buried piping circuit with parallel-connected double U-tube boreholes.

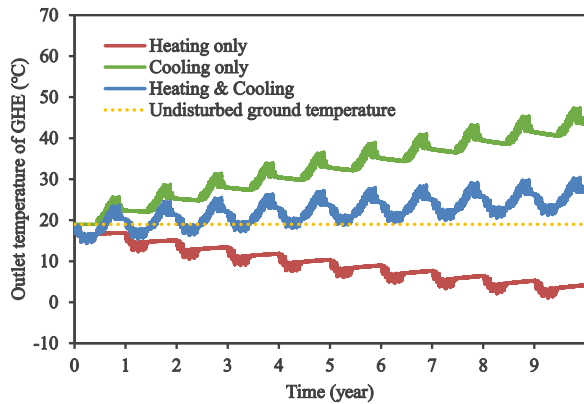


Figure 8: Outlet temperature of GHE in multi-year simulation.

The monthly electricity consumption of the reversible GCHP system is shown in Figure 9. When running in heating only mode, the electricity consumption increases over the years because the ground temperature decreases, inducing a lower COP. While operating in “cooling only” mode, there is no heating load balancing, and the

increase in ground temperature induces an increase of the electricity consumption year by year as well. In “heating and cooling” mode, the ground temperature increases over the years, leading to decreasing electricity consumption in heating seasons and increasing electricity consumption in cooling seasons. Despite the fact that the ratio of heating and cooling loads is close to 1, COP in heating season is higher than that in cooling season. Taking the first year as an example, the average COP for the heating season is 5.2 and the average COP for the cooling season is 4.1. Therefore, GHE discharges more heat to the ground than it absorbs throughout a year, leading to an annual increase in ground temperature. This temperature rise increases the efficiency of the GCHP during the heating season and decreases the performance during the cooling season. Therefore, there is a year-on-year reduction in electricity consumption during heating seasons, but a slight increase during cooling seasons.

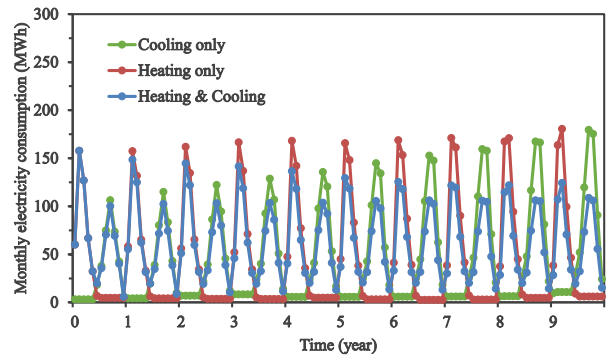


Figure 9: Monthly electricity consumption of reversible GCHP system.

Environmental impacts of electricity consumption with a different time resolution

From dynamic electricity consumption obtained using COMFIE and a GCHP model, environmental impacts of the power consumption over the 20-year operation stage can be quantified by aggregating the energy consumption per technology per unit timestep weighted by the environmental impact of 1 kWh electricity produced by each technology, as expressed in Equation (2):

$$EI_{total,electricity} = \sum_{t=1}^k \sum_{i=1}^{11} (E_t \times R_{i,t} \times I_i) \quad (2)$$

where i represents eleven different technologies, t represents the t th time step in the total time step k during the system operation stage, E_t represents electricity consumption of reversible GCHP system at timestep t , $R_{i,t}$ represents the share of technology i at timestep t , and I_i represents the life cycle impacts of 1 kWh electricity supplied by technology i . In this study, time steps of one month, one trimester, and one year were chosen to evaluate the effect of different time resolutions on LCA results.

The comparison of environmental impacts over 20-year using monthly/trimestral/annual time steps is shown in Figure 10 for the selected twelve indicators. The results using monthly electricity mix and monthly electricity

consumption data (over 20 years) were considered to have the highest accuracy as a reference for comparison. Due to the small differences in the results, the coordinates selected for the radar plots in this section range from 0.9 to 1.02 to better observe the variation of each indicator. It can be observed that the discrepancy between results using 20 years of trimestral data and 20 years of monthly data is insignificant. All indicators were slightly underestimated, ranging from 0 % (Abiotic Depletion Potential) to 4.4 % (Eutrophication Potential), with an average underestimation of 1.4 %.

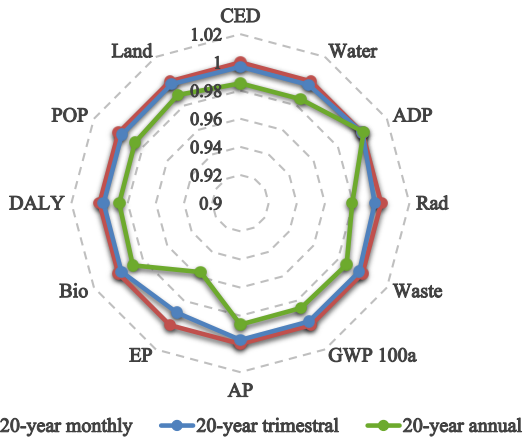


Figure 10: Impact assessment of electricity consumption with monthly/trimestral/annual time steps.

Considering that the long-term performance degradation of the GCHP system was not taken into account in the general LCA studies, results of the environmental impact assessment using only one-year energy consumption data and the 20-year energy consumption data were compared, as displayed in Figure 11. It was shown that compared to the results with 20-year monthly energy consumption data, using 1st year monthly and trimestral energy consumption data leads to an average underestimation of around 5 % for all indicators. It is noteworthy that using annual data from the 1st year results in an average underestimation of 6.5 % and up to 9.2 % in Eutrophication Potential.

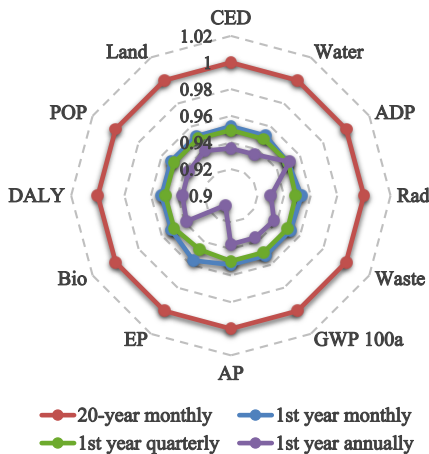


Figure 11: Impact assessment of electricity consumption with/without considering long-term performance degradation (different temporal resolution).

A comparison of the effects of considering multi-year performance degradation at the same resolution was also conducted, as shown in Figure 12. Environmental impacts calculated using 1st year annual/trimestral/monthly energy consumption data was separately compared with environmental impacts calculated using 20-year annual/trimestral/monthly energy consumption data. At the same temporal resolution, the results for environmental impacts exhibit similar levels of underestimation for the 12 indicators, with monthly, trimestral, and annual underestimation averages of 4.8 %, 4.8 %, and 5.0 %, respectively.

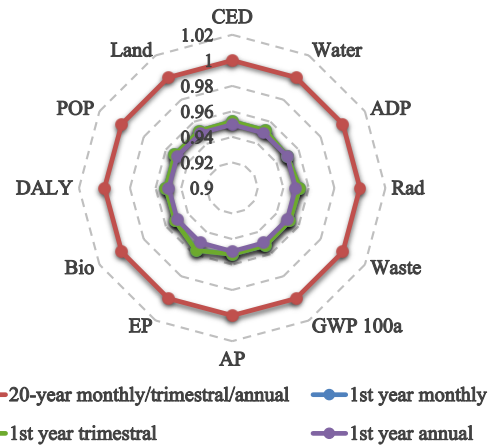


Figure 12: Impact assessment of electricity consumption with/without considering long-term performance degradation (same temporal resolution).

Taking a deeper look at the share of different technologies in each indicator provides insight into the factors contributing to the variation in indicator across different time resolutions, as shown in Figure 13. It can be observed that the final environmental impact share of Eutrophication Potential is mainly due to oil (59 %), whereas hydropower represents only 13 %, which is significantly different from the other indicators. The share of thermal and hydropower in Wuhan's electricity mix fluctuates notably by month and season. For the Eutrophication Potential indicator, the impacts of oil power plants (which represents 8.3 % of thermal power) are much larger than the impacts of hydropower. This explains the relatively greater impact of the annual average data.

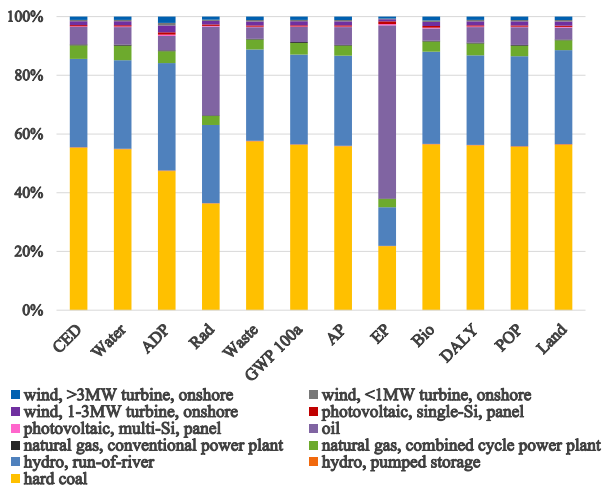


Figure 13: Contribution of different technologies in the 12 indicators.

LCIA results of a reversible GCHP system

LCA results regarding manufacturing and installation were calculated using Brightway2/Activity-browser (Steubing et al., 2020) and data collected from the Ecoinvent v3.4 database. Environmental impacts related to electricity consumption during the operation stage were then included to get the final results. It should be noted that the technical life span is assumed 100 years for borehole heat exchanger and heat collector (Violante et al., 2022), which allows for five operational life cycles of the heat pump. Therefore, in this study, the environmental impact of the borehole heat exchanger and heat collector was correspondingly equated to one-fifth of the total for a 20-years study period. Figure 14 shows the relative contributions of the four technological elements (heat pump, borehole heat exchanger, heat collector, and electricity) to the total scores within each indicator.

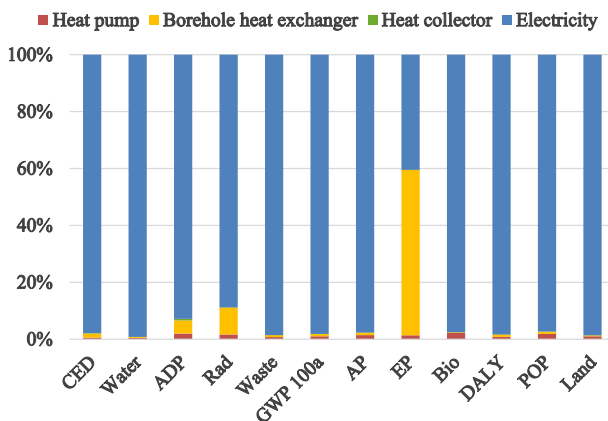


Figure 14: Relative contributions of a technological element to the 12 indicators.

Electricity required for heat pump operation is the dominant factor in 11 out of 12 indicators, contributing between 89 % and 99 % to the total, which is consistent with previous findings. The Eutrophication Potential on the other hand is primarily related to the borehole heat exchanger. This is mainly due to the massive heat carrier

liquid needed in the double U tube and diesel consumed for the drilling during the installation stage.

Discussion

A dynamic life cycle assessment with different temporal resolutions was conducted in this paper to compare the environmental impacts of a reversible ground source heat pump system designed for a large residential building in Wuhan. The overall monthly and annual differences are negligible in this case study. On the other hand, the variations caused by the degradation of system performance with time are significant. Several outlooks and reflections on this study are listed below.

- The findings (Figure 10 and Figure 11) suggest that monthly fluctuations in the electricity mix could change the estimation of different indicators. Thus, it is necessary to further analyse the local generation patterns, so that we can better understand its driving factors.
- The fluctuations in electricity mix and electricity consumption deviating from the mean at high temporal resolution (monthly) is responsible for errors in the results at low temporal resolution (annual). Since the system provides both heating and cooling loads, most of the time its monthly power consumption does not deviate significantly from the average value. But when the system is used only for heating or cooling, the variations in results are increased, so the choice of temporal accuracy partly depends on the end use of the system.
- The electricity mix of Hubei Province for one complete hot and cold season from 2021 to 2022 was selected for the study and assumed to remain constant during the operation stage of the system. However, in real life, the electricity mix evolves over years and the building cooling and heating loads also vary with weather and climate change. Therefore, performing prospective analysis would also be a possible direction.
- The impact caused by the imbalance between building heating and cooling loads can be mitigated to some extent by employing heat pump systems to provide domestic hot water in winter.

Conclusion

In this paper, a reversible GCHP model is coupled to the dynamic building energy simulation tool COMFIE to generate hourly energy loads over the life span of the system. Benefiting from monthly electricity mix data, an LCA methodology was proposed to improve the precision of LCA results by considering performance variation of the GCHP system affected by building heating and cooling loads. Results demonstrate that when the long-term performance degradation is considered, the variation induced by the time resolution of the electricity mix data is limited. However, if this performance degradation is not considered, the use of an annual average mix and electricity consumption instead of monthly and trimestral data can lead to an

underestimation of potential impacts up to 9.2 % for Eutrophication Potential. The apparent reduction in EP at annual time resolution can be attributed to monthly relative fluctuations between thermal and hydro technologies in the Wuhan electricity mix. To summarise, taking into account long-term performance degradation of the system is important for a precise evaluation of the potential environmental benefits of GCHP systems. In this case study, considering the variable electricity mix did not lead to significant difference, however it should be considered in case where there is a stronger variation in monthly electricity consumption. This study can provide a reference for future LCA studies of other systems according to their use and local electricity mix.

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