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Energy and environmental implications of using geothermal heat pumps in buildings: An example from north China

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ABSTRACT

Integration of renewable energy technologies and buildings is a step toward more energy efficient buildings in China. However, the life-cycle of energy and environmental emissions associated with geothermal resource use in buildings is not well understood. This study quantifies the life-cycle energy consumption and environmental pollutant emissions of geothermal heat pump (GHP) deployment in China using a university building as an example. A process-based hybrid life cycle inventory (LCI) modeling approach was used to enable a comprehensive system boundary for footprint accounting and to provide specific insights for the design and operation of the geothermal technology. The life-cycle energy of the GHP system was 192 TJ, and the life-cycle SO_2, NO_x, and greenhouse gas (GHG) emissions were estimated at 35 metric tons (MT), 45 MT, and 19130 MT CO_2e. The annual operational energy use of the GHP was 6.2 and 4.1 kWh per square meter floor area for building heating and cooling respectively. This was an energy use reduction of 84% and 83% compared to municipal heating and air conditioner cooling. The energy and GHG payback times of the GHP systems were 0.5 and 0.3 years respectively, and the facility is estimated to be economically cost-effective in 7.4 years.

1. Introduction

The challenges of energy conservation and environmental sustainability are complex and urgent. Buildings, along with industry and transportation, are major energy consumers especially in developing economies like China that are experiencing rapid urbanization and rising living standards (Chang et al., 2011). The urbanization rate of China was 54% in 2015 and is projected to reach 70% by 2030 (UNDP, 2013). As a result, China's urban population is expected to grow by 20 million every year, and more than four billion square meters (m^2) of buildings have been built annually since 2013 (NBSC, 2015a). The energy use associated with the manufacture of building materials and building construction (i.e., building embodied energy) comprises approximately 21% of China's total energy consumption (Chang et al., 2011), and an additional 20% is added if various energy end uses such as heating, cooling, cooking, and illumination during building operation (i.e., building operational energy) are included. Because of the long average period of building use (usually 50–70 years), operational energy consumes at least 80% of the building life-cycle energy (Chang et al., 2013). The annual operational energy per unit (1 m^2) of a residential building in China is 440 MJ, which is only 33%–43% the consumption used for a comparable building in developed countries such as U.S. and U.K. (BEERCT, 2014). However, increasing household income and rising living standards in China will increase household energy use. This is expected to result in 140% building energy growth from 2000 to 2020 (Zhou et al., 2008).

Building life-cycle energy consumption relies heavily on the use of electricity. This increases the deterioration of air quality in China because the electric power supply is heavily dependent on the burning of coal. The substantial consumption of coal-fired electricity and heat for building services has led to severe haze formation and increasing greenhouse gas (GHG) emissions (Wang et al., 2017). GHG emissions from coal-fired electricity average 980 kg CO_2e/kWh in China which is significantly higher than emissions from natural gas-fired and nuclear electricity. However, the environmental footprints associated with natural gas and

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nuclear energy use are still higher compared to renewable technologies such as wind, solar, and ocean energy. These renewable technologies will lead to a cleaner energy supply in China (Chang et al., 2015). And the integration of renewable energy technologies with building designs is an important pathway for a more sustainable built environment in China.

Renewable energy sources will contribute to expanding the energy supply and mitigating air pollution in China because of their limitless reserves and low-carbon content. Renewable energy includes biomass, solar, wind, ocean, hydro, and geothermal. Commercial applications focus on liquid fuel generation (such as ethanol, methanol and biodiesel), electricity generation, and heat production (IPCC, 2011). For buildings, renewable technologies are deployed for electricity and heat provisions to satisfy occupant demands and basic services such as hot water, space heating, and cooling. Several studies have summarized the status, challenges, and opportunities of geothermal heat pump utilization in buildings (Geng et al., 2013; Liao et al., 2016), analyzed computational and simulation models to optimize GHP designs (Yuan et al., 2012; Ni et al., 2015), identified critical parameters that affect the operation performance of GHP systems (Zhang et al., 2016; Liu et al., 2017), and assessed the environmental and economic benefits derived from GHP technology applications (Huang and Mauerhofer, 2016). However, compared to the knowledge of solar and wind technologies, there is inadequate understanding of the energy and environmental footprint of geothermal heat pumps. Existing analyses mainly focus on the design and operation of GHP systems. The life cycle phases of material and equipment manufacturing, transportation, and facility construction and installation have not been completely considered. As a result, detailed inventory data about GHP system material and equipment inputs are lacking in China, limiting bottom-up analyses of the energy and environmental impacts associated with GHP applications. To help fill these knowledge gaps, this study used the hybrid life cycle inventory (LCI) modeling approach to quantify the life-cycle energy and environmental emissions associated with integrating a geothermal heat pump into an educational building in Shijiazhuang Tiedao University in north China. The results help to identify the energy and environmental opportunities in the GHP life cycle, increase understanding of ways to deploy GHP in buildings, and contribute to green building development in China.

2. Study framework

To calculate the energy and environmental emissions associated with GHP deployment in buildings, we developed a process-based hybrid LCI model to enable both comprehensive system boundary for footprint accounting and specific calculations for the design and operation of the case technology, see Fig. 1. The input-output (I-O) LCI modeling approach is used to calculate the energy and environmental footprints of material and fuel inputs of the geothermal heat pump systems. The process LCI model is used for estimating the footprints of material transportation, facility construction, and

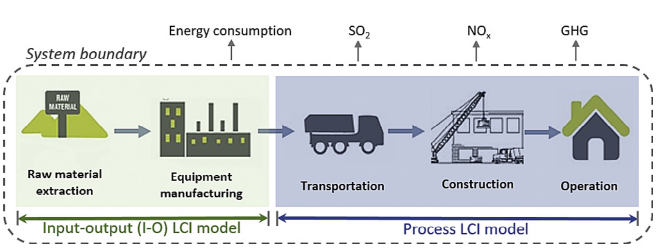

Fig. 1. Boundary of the geothermal heat pump (GHP) systems.

operation. The lifespan of the geothermal heat pump consists of five phases. These are raw material extraction, equipment manufacturing, transportation, construction, and operation. Given the insignificant quantity of the GHP unit and relevant accessories such as water tanks and boilers, the recycling and reuse of the geothermal heat pump systems was not considered.

The I-O LCI model was used to calculate the energy and emissions of raw material extraction and equipment manufacturing due to the model's strength in comprehensive system boundary for footprint accounting. Based on economic input-output technique developed by Wassily Leontief (1970), the I-O LCI model calculates the total supply chain energy and emissions of products within a specified economy and avoids the subjective and limited system boundaries defined by different researchers (Hendrickson et al., 2006). Using the I-O LCI model, the cross-sector supply-chain footprints of certain product can be calculated: $F = S(I\text{-}A)^{-1}d$, where F is the supply-chain energy and environmental footprints, S is the satellite matrix and its element $s_{i,j}$ denotes the intensity of sector j for impact i (i.e., the energy consumption or emissions of sector j's per unit monetary output), I is the identity matrix, A is the technical coefficient matrix, and d is the final demand vector (Hendrickson et al., 1998; Heijungs and Suh, 2002).

The I-O model used here is based on the 2012 China input-output table (NBSC, 2015b), which is currently the latest economic benchmark of statistics in China. Despite the time lag of the I-O model, we used this modeling approach because of its strength in economy-wide calculation of the energy and environmental footprints of material and equipment associated with GHP utilization, i.e., it quantifies the total-supply-chain footprints of the GHP system inputs and identifies the source footprint sectors, shedding light on opportunities for reducing the energy and environmental burdens associated with GHP scale deployment in buildings. In developing the I-O model, the sectoral energy consumption, SO_2 and NO_x emissions were obtained from the national statistical yearbooks (NBSC, 2013; NBSC and MEP, 2013). The sectoral CO_2 emissions provided by the China emission accounts and datasets (CEADs, 2015) were used. Sectoral CH_4 and N_2O emissions were estimated in a bottom-up manner, including direct emissions of fossil energy combustion and indirect emissions derived from the processes of mining, agriculture, and livestock husbandry. The methods and emission coefficients of previous studies are referenced (Zhou et al., 2007; Zhang and Chen, 2014; Zou et al., 2010; Chen and Zhang, 2010).

Given the high sectoral aggregation of I-O tables, an assumption of homogeneity is normally made (Nässén et al., 2007; Chang et al., 2010) when calculating the sectoral energy and emissions coefficients, i.e., the energy consumption and emissions per unit of the sectors monetary output. This would introduce uncertainty in the model results, but is regarded as acceptable because products of the subsectors of a given parent sector have high similarity compared to those of other sectors in the economy systems. For the case of GHP systems, the monetary cost of materials and equipment were calculated by their unit price and consumption quantities obtained from building documents and design drawings. The price data is at the 2012 China price level and is consistent with the benchmark I-O table, so price adjustments are not needed.

The I-O LCI model yields national average footprints for a broad category of similar products, lacking specificity for individual products and services, and the approach is inapplicable for estimating product operation and use (Hendrickson et al., 2006). Therefore, the materials and equipment transportation, facility construction and installation, and GHP systems operation were modeled by process LCI approach to enable footprint calculations that were specific to the case technology. Detailed modeling and calculations are presented in section 3.2 and 3.3.