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Life cycle sustainability assessment of ground source heat pump in Shanghai, China

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ABSTRACT

The growing worldwide demand for Greenhouse gas (GHG) emission reduction has led to a new age of energy saving. Besides the energy saving extent, the costs of energy saving measures as well as the environmental and social impacts are also necessary to be evaluated in order to make sure that the application of these measures can also meet sustainable development requirements. Thus, a sustainability evaluation method based on Life Cycle Theory is innovatively designed in this study. We present its new aspects, describe its working steps in detail and also test this new method by means of a case study on Ground Source Heat Pump (GSHP), which is a renewable technology that is widely applied in the building sector in China. Data for the case study is collected by literature review and site investigation. Results show that the energy consumption of the investigated GSHP cases has an energy saving rate as around 40.2%.The main environmental impacts of GSHP are found to be global warming, acidification and eutrophication in the production process, and soil temperature change in the operation process. The prevention cost of the environmental impacts is around 15.84 RMB/m^2 in the production process, and 5 RMB/m^2 in the operation process. The payback time of our cases is around 4 years, and it will rise to 4.29 years if accounting the environmental prevention cost. We conclude based on the case study that our assessment method proofs to be useful as it can demonstrate comprehensive characteristics of sustainability for energy saving measures in the whole life cycle.

1. Introduction

The growing worldwide demand for GHG emission reduction has led to a new age of energy saving during about the past three decades. Within this period, the building sector is estimated to have great energy saving potential, especially in developing countries which are experiencing a construction explosion in the ongoing decade (Jiang and Tovey, 2010). China's energy policy focuses on sustainable energy supply and the reduction of the overall intensity of carbon emissions by increasing the proportion of renewable energy use in the building industry (Zhou, 2012). Ground source heat pump (GSHP), often referred to as geothermal heat pump (GHP), offers an attractive option for heating and cooling residential and commercial buildings due to their higher energy efficiency compared with conventional systems (Hepbasli and Akdemir, 2004). Omer (2008) reviewed the worldwide application of geothermal energy for direct utilization and concluded that GSHP had almost 59% growth rate since 1995. Most of this growth occurred in the United States and Europe. Research on and practice of GSHP in China started much later than that in developed countries. The end of 1980s saw the beginning of experiments and tests on the performance of the GSHP systems. Qingdao Technological University, Tianjin University of Commerce and Tianjin University are the first three universities, which conducted relevant research on GSHP technologies. At the end of 1990s, theoretical and experimental studies in all aspects of GSHP were carried out, mainly supported by the National Natural Science Foundation of China. Some significant achievements have been attained ever since, so that the application and development of GSHP systems are being boosted greatly. The beginning of the 21st century is a period of rapid growth of the application of GSHP systems (Yang et al., 2010). According to a Feasibility Analysis Report of the related industry (China Geothermal Heat Pump Industry, 2013), there are already more than 5000 GSHP projects existing in China. In Shanghai, there are over 500 projects. Although GSHP system is widely developed

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in China, it is claimed as a controversial technology due to its high investment cost. In recent years, the already existing Chinese projects also reveal environmental side effect such as soil temperature change (Yang et al., 2010).

Some studies have been carried out to assess the energy performance of GSHP. Sanner et al. (2003) indicated that each kWh of heating or cooling output of GSHP system currently require 0.22~0.35 kWh electricity in Europe, which is 30~50% less than the seasonal power consumption of air source heat pumps. Ozturk (2014) analyzed the energy efficiencies of a combined GSHP-system whose evaporator component works as a photovoltaic-thermal collector and found that the coefficient of performance (COP)[1] of the system is 2.9 and found that the mix system has higher energy efficiency than traditional GSHP system. Other research evaluated the environmental impact of applying GSHP. Saner et al. (2010) examined environmental burdens and benefits related to applications of geothermal systems by employing life cycle assessment and found that the main environmental influences are resource depletion and ecosystem quality. Wang et al. (2014) conducted research on life cycle environmental impact assessment of ground source heat pump, and their results show that more than 60% of resource consumption potential, acidification potential, and global warming potential derived from the process of underground construction. In respect of the economic evaluation of GHSP, Nagano et al. (2006) found for their example in Sapporo, Japan that the payback time for increased investment cost of GSHP system is 10 years in comparison with the oil boiler and the air condition (AC) system, 9 years in comparison with the gas boiler and the AC system, and 14 years in comparison with the air condition heat pump (ASHP) system. Esen et al. (2006) presented a detailed cost analysis with payback periods when substituting for different local fuel/power sources in one case in Turkey. They indicated that payback period of the GSHP would be 8.38 years against the electric systems. Most of the existing research evaluated the energy, environmental and economic performances of GSHP respectively. This situation also exists in the assessment of other energy saving measures. Some researchers focus on environmental impact evaluation of energy saving measures (Arena and Rosa, 2003; Khasreen et al., 2009; Wang et al., 2014). Others carry out assessments of the economic efficiency for energy saving measures (Bernstein et al., 2006; Kneifel, 2010; Ren and Gao, 2010). Researchers such as Wang et al. (2010) implement the social effect assessments for energy saving measures, and found that the main social effect is promotion of employment rate, especially for renewable technologies. Recently others try to assess mixed indicators for technologies based on life cycle theory. For instance, Vasquez et al. (2015) analyzed the GHG emission reduction and environmental influences such as acidification and eutrophication for solar water heat systems considering the production, use, maintenance and end-of-life stages. Lamnatou et al. (2015) evaluated environmental impact and energy saving of a building-integrated solar thermal collector by means of the life cycle assessment methodology IMPACT 2002+.[2]

[1] That is an indicator that describes the efficiency of GSHP. It a ratio of heating or cooling provided to electrical energy consumed. Higher COPs equate to lower operating costs. COP is highly dependent on operating conditions, especially absolute temperature and relative temperature between sink and system, and is often graphed or averaged against expected conditions.

[2] IMPACT 2002+ is a methodology that was originally developed at the Swiss Federal Institute of Technology Lausanne (EPFL), Switzerland. The life cycle impact assessment methodology IMPACT 2002+ proposes a feasible implementation of a combined midpoint/damage-oriented approach. More information can be found at http://www.quantis-intl.com/impact2002.php.

However, none of the reviewed literature provides a method that can demonstrate comprehensive characteristics of energy saving measures in the whole life cycle. Considering the energy saving and the costs of energy saving measures are necessary to be analyzed together with the environmental and social impact in order to make sure that the application of energy saving measures can also meet sustainable development requirements (Huang et al., 2012), a more reasonable evaluation method is of significance for optimal technology selection. Consequently, a sustainability evaluation method based on Life Cycle Theory is designed to evaluate the sustainability of GSHP technology in China as a case study. In the following parts of the paper, an overview on the methodology is provided next. Therein, we first define “sustainability” and the boundary for our LCA assessment. Secondly, we describe some additional technical background of GSHP. Thirdly, we inform about the case study and its data source. As a fourth step we describe how this innovative assessment is applied in general and in particular within the case study. After this description of the methodology, the results of the case study are presented. This presentation is followed by a discussion of the methodology as well as of the results.

2. Methodology

2.1. Sustainability definition and evaluation boundary

Sustainable development goals are usually defined as economic development, social development and environmental protection (United Nations General Assembly, 2005). For an energy saving measure, a high sustainability level means it should be economically efficient, have an environmental impact including a valid energy saving and little or no negative influence, and should have positive social effect (Huang et al., 2012).

For a specific energy saving measure, the economic costs are occurring in the whole life cycle, while energy saving is achieved during the operation process. In comparison, the environmental impact can occur in the production, installing, operation and demolition processes. The social effects such as employment contribution happen also in the whole life period. As shown in Fig. 1, we can find a quite distinguished distribution of cost and impacts in chronologic terms for specific energy saving measures.

In our paper, it provides the innovative basis for the assessment of GSHP on the example of a case study. Because of the data availability limitation, the demolition process is not considered in our case study presented later. Due to the same reason, the environmental influence of GSHP in the installing process is not included.

2.2. Case study and data source

Two basic configurations of GSHP can be differentiated, namely ground coupled heat pump and ground water heat pump systems (Omer, 2008). In Southern China, the ground water level is relatively high, and the liquid heat transfer has high quality effect, which makes the ground coupled GSHPs most commonly adopted (Tang and Zhang, 2011). Thus, we will focus on evaluation of ground coupled GSHPs in this paper. Twenty buildings applying GSHP systems in Shanghai are investigated in our study, including ten commercial buildings and ten residential buildings. They are almost located in Huangpu and Yangpu district of Shanghai. The building areas of these selected residential buildings are in the range of 800~1500 m^2, commercial buildings are in the range of 2000~3000 m^2. Other information can be found in the Appendix.

The cases are selected according to investigation convenience and data availability. The investigation is cooperated with and