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A comparison of deterministic and probabilistic life cycle cost analyses of ground source heat pump (GSHP) applications in hot and humid climate

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ABSTRACT

Geothermal energy is widely considered as an ideal alternative energy for building operations. Despite the fact that ground source heat pumps (GSHPs) have been studied for decades, including economic analyses such as life cycle costing, their technical and economic applicability in hot and humid climate such as FL, USA is yet to be determined. In the past, many life cycle cost analyses on GSHPs were conducted using a deterministic method to derive point estimates. In many cases, data were assumed, but data uncertainties were not accounted for. In this study, a comparison of the deterministic and the probabilistic method was performed in order to understand the impact of data uncertainties on results of analyses. The probabilistic life cycle cost analysis was based on Monte Carlo simulation. A GSHP application case in Pensacola, FL was selected for the comparison. Some data were collected through site visits or interviews, while others were gathered from the literature or published data. Probability distribution functions used by Monte Carlo simulation were derived based on historical data or assumptions. Results of the case study from both deterministic and probabilistic methods confirmed that the GSHP option was economically more favorable than a conventional single zone split system using heat pumps, but with a long payback time if incentives were not considered. The probabilistic method was found to deliver a more reliable conclusion with more critical information than the deterministic method. However, further studies were needed to verify those initial observations obtained from this case study.

1. Introduction

According to Griffith et al. [1], about one third of the world's energy was consumed by buildings and their operations. They also pointed out that this number could continue to increase as the world population became more urbanized. In the USA, the building sector accounted for 40% of the primary energy consumption. In addition, buildings accounted for 40% of total CO_2 emissions, 12% of water, 68% of electricity, 55% natural gas consumption, and 60% of non-industrial waste [2]. If this trend continued, the buildings sector would have a larger energy and CO_2 emission footprint than transportation and other industry sectors. Interestingly, reducing the consumption of energy in buildings was the least costly way to achieve large reductions in carbon emissions [3]. The significant energy consumption by the building sector has led to the quest for alternative energy sources, including solar, wind and geothermal energy.

According to the National Science and Technology Council [4], if ground energy sources were used effectively, they could significantly reduce peak loads and save energy from conventional sources. Such technology could also be used in combination with other technologies to be more efficient and effective. Ground source heat pumps (GSHP) also known as geothermal heat pumps utilize relatively constant temperatures found underground and the stored thermal energy of the earth to condition building spaces. Hughes [5] compared three estimates of energy savings from the application of GSHPs. The study reported that GSHPs could generate seven to eight percent of savings. However, there were barriers to realize the economic benefits. Through surveys, the study also found that higher first-cost of GSHP systems to consumers was one of the major barriers.

On the other hand, other studies examined the application of GSHPs from an economic perspective. For example, Erdogmus et al. [6] performed an economic assessment of geothermal district heating systems in Turkey based on a life cycle perspective. Life cycle cost analysis has been applied to many building or energy related studies. For example, Halwatura and Jayasinghe [7] applied life cycle costing to a study analyzing the impact of insulated roof slabs on air conditioned space in tropical climatic conditions. Agrawal and Tiwari [8] presented a study on the life cycle cost of building

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integrated photovoltaic thermal systems. However, many of those life cycle cost analyses used a deterministic approach. Especially, in geothermal systems related studies, many studies were dated back decades. For example, Shonder et al. [9] performed a life cycle cost study of applying GSHPs to K-12 schools in Lincoln, NE. Their study showed that GSHPs were the most cost-effective option over four other alternatives. Bloomquist [10] concluded that operational and maintenance savings from GSHPs were significant comparing with conventional systems based on life cycle costing. Also using life cycle costing, Chiasson [11] compared three HVAC systems proposed for a new office building on the Winnebago Reservation in northeastern Nebraska. The study showed that the GSHP option had the lowest life cycle cost, followed by rooftop units with gas heating and direct expansion (DX) cooling and then air-source heat pumps.

These studies were focused on applications in cold and dry climate regions. Such findings seemed against common wisdom, which ruled that it was unwise to use geothermal heat pump systems for cooling in hot and humid climate. However, some studies have reported effective applications of GSHPs in hot and humid climate. For example, Im and Haberl [12] presented a survey of high performance schools in hot and humid climate and found that GSHPs were frequently adopted by schools to save energy. More recently, Melby et al. [13] reported that using geothermal systems saved 45–55% on heating and cooling costs for residential homes in hot and humid climate.

Thus, apparently the applicability of GSHPs in hot and humid regions such as FL, USA is yet to be determined. In addition, accurate energy or economic analyses rely on the quality of data. Unfortunately, data uncertainty is a well-recognized issue associated with previous studies on GSHPs. Uncertainties may be resulted from many cost items involved in a life cycle cost analysis, such as initial costs, maintenance costs and electricity rates. All of the aforementioned life cycle cost analyses used a deterministic approach, in which data uncertainties were ignored. It is thus interesting to know if considering data uncertainties will generate a different result from a deterministic life cycle cost analysis.

The objective of this study is to compare a deterministic life cycle costing method with a probabilistic life cycle costing method based on Monte Carlo simulation to account for data uncertainties. Through such a comparison, it is expected to better understand if the probabilistic method will significantly change, hopefully enhance, results derived by using the conventional deterministic method, and if distributions of sensitive cost factors will significantly alter results as well. Such understandings can be very useful for conducting future life cycle cost analyses on ground source heat pumps.

2. Research approach

To achieve the objective of this study, a case study in FL, USA was selected so that comparisons of the two methods could be made. The selection of the case was based on data accessibility and owner's willingness to participate in the study. In addition, a hypothetical base case was established based on the case study, i.e. using the same building data, except that the HVAC system was assumed to be a conventional system, a split system with air source heat pumps of the same capacity. Both deterministic and probabilistic methods were applied to the real and the hypothetical case. Then results derived by using the deterministic method was compared with the one derived by using the probabilistic method to find answers to the research questions.

In this study, cost elements and factors involved in a life cycle cost analysis were first determined by reviewing existing life cycle costing methods. Then data sources were identified and selected. Initial costs of the GSHPs were collected from site visits and interviews with the owner of the facility. The owner did not have sufficient maintenance and replacement cost data since the facility was fairly new. Thus, these costs were estimated according to literature and standard data sources such as R.S. Means Facility Maintenance and Repair Cost Data. Energy costs of building operations were estimated based on the simulation of electricity consumption and the electricity rate in that area. The simulation was corroborated by using real electricity consumption data collected from the facility. For the hypothetical conventional system, the initial cost data were derived based on an estimate using the R.S. Means Assembly Cost Data. The estimate was compared with vendor quotes to ensure acceptability. Maintenance and replacement costs of the conventional system were also estimated based on literature and R.S. Means Facility Maintenance and Repair Cost Data. Energy cost of the conventional system was estimated based on the simulation of electricity consumption as well.

The conventional life cycle cost analysis method has been discussed for decades, thus details will not be provided in this paper. The probabilistic method requires a probability distribution function to account for uncertainties associated with data. The development of distribution functions needs repetitive experiments, which was difficult to conduct in this case. Thus, alternatives were applied, i.e. using commonly assumed distribution functions discussed in literature or developing a distribution function based on historical data of the same type of data. Details were provided later in another section of this paper.

Once data and probability distribution functions are ready, a life cycle cost analysis can be performed. In this study, a software tool, @Risk, was used to perform the Monte Carlo simulation for the implementation of the probabilistic method. The conventional method was performed using Microsoft Excel.

3. Probabilistic life cycle cost modeling

Since cases of conventional life cycle cost analysis had already been well documented (e.g. [9–13]), this paper was focused on the probabilistic life cycle cost analysis based on Monte Carlo simulation. In the following, a literature review on Monte Carlo simulation and its applications in construction was first provided. Then, the modeling of probabilistic life cycle costing was discussed in details.

3.1. Monte Carlo simulation and applications

Monte Carlo simulation is often used as a tool to consider uncertainties in data while conducting certain analysis. It has been applied to many fields of project management including project cost estimating [14] and scheduling [15,16]. This is because point estimates of project cost or durations are questionable when in reality there are uncertainties associated with data and processes applied to a calculation procedure for cost and durations (e.g. [17]). Elkjaer (2000) discussed a stochastic budget simulation method that used triple estimates to account for uncertainties (i.e. minimum, most likely and optimum values of any cost time), predefined probability distributions to generate data (e.g. triangle distributions or Erlang-5 distributions), and Monte Carlo simulation to enhance estimate results. Wang [18] applied a probabilistic estimating method to project cost. In that study, the triple estimate method was also used and a beta statistical distribution was applied to each cost component under study.

Monte Carlo simulation has been applied to life cycle costing. For example, Walls and Smith [19] proposed using Monte Carlo simulation to account for uncertainties in life cycle costing of pavement. They suggested that both subjective and objective methods could be used for developing probability distribution functions for variables in life cycle costing. When data were available, the