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Energy and cost analyses of a hybrid renewable microgeneration system serving multiple residential and small office buildings

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HIGHLIGHTS

- Examine energy and cost performance of a hybrid GSHP–FC microgeneration system.
- The system has lower annual primary energy consumption compared to a GSHP system.
- It reduces buildings' dependency on the electricity grid.
- It could achieve cost savings if natural gas to electricity price ratio is low.
- The extra capital cost incurred is possible be returned within system's lifespan.

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ABSTRACT

This study investigates the energy and cost performance of hybrid renewable ground source heat pump (GSHP) and natural gas fueled fuel cell (FC) microgeneration systems serving multiple residential and small office buildings in Ottawa (Canada) and Incheon (South Korea). The study is performed by simulations in TRNSYS environment. The performance of the microgeneration system is compared to a GSHP only system. In addition, the impact of the FC capacities, natural gas price and electricity price on the system's energy and cost performance is examined.

The energy analysis results show that the GSHP–FC systems have less primary energy consumption compared to the GSHP only system in both geographic locations. However, whether a GSHP–FC system could achieve operational cost saving is strongly dependent on the local natural gas and electricity prices and also on the building heating, cooling and electrical loads and their patterns. The GSHP–FC microgeneration systems could yield operational cost savings at locations where the natural gas (or other input fuel to the FC) price is much lower than the electricity price, such as in Ottawa. At locations where with exceptionally high natural gas to electricity price ratio, such as in Korea, no operational cost saving could be attained by the GSHP–FC system.

The cost analysis results indicate that, in Ottawa, the extra capital investment incurred to the GSHP–FC system is possible to be returned within its lifespan, especially with the current trend of continuous price reductions of FC equipment and installation resulting from economy of scale and market expansion. Nevertheless, the GSHP–FC microgeneration systems' capability to generate both electricity and thermal energy at the point of use is generally considered more attractive for inclusion in the "smart" energy networks, new and remote community applications.

1. Introduction

Microgeneration systems able to produce both heat and power at the point of use are beginning to emerge as a viable alternative to the large and expensive central power generating stations. Recently, the frequent blackouts around the world [1] have increased public awareness and interest in on-site small size generation (1–30 kWe) mainly due to the high efficiency performance, good environmental footprint and suitability to serve as both primary and back-up power generation [2–27]. These systems are becoming even more attractive for new and remote community applications where costly construction of central generation stations and connection to the grid is neither affordable nor a preferable option [28,29].

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Microgeneration systems are in size of 1–30 kWe and less than 50 kWth and are designed to satisfy all or part of the power/heating demands of a typical building or a group of buildings. Most of microgeneration systems can be integrated in smart energy networks and applied for both on-grid and off-grid applications. The systems are designed to recover the heat produced during the electricity generation process with consequent use for space and water heating in winter and in some cases thermal cooling in summer. Although microgeneration is an exciting emerging technology, it faces many challenges, for example in gaining market share in mature and competitive markets for domestic and commercial boilers, in further improving devices' efficiency and reducing cost, in increasing the operational life-time to recover the initial investment, and also in obtaining understanding of the technology both by installers and potential end users.

Among these microgeneration research [2–27], some [10–16,24–27] have studied hybrid microgeneration system with integration of renewable energies. Fuel cell (FC) based microgeneration systems gained a wide range of interests due to their potential to operate with higher electrical efficiency. However, among many FC microgeneration researches [17–27], most were focused on one technology or comparison of different technologies. Only few have studied hybrid systems with integration of FC and geothermal source [24–27]. Currently, Annex 54 of the International Energy Agency's Energy in Buildings and Communities Programme (IEA/EBC) is undertaking an in-depth analysis of microgeneration and associated other energy technologies [30]. The Annex 54 includes, among many research activities, study of multi-source micro-cogeneration systems, polygeneration systems and renewable hybrid systems, and analysis of integrated and hybrid systems performance when serving single and multiple residences along with small commercial premises [30].

To fulfill part of the IEA/EBC Annex 54's objectives, Entchev et al. [31] investigated the performance of an integrated ground sources heat pump (GSHP) and natural gas fueled fuel cell microgeneration system in load sharing application between a detached house and a small office building. The study shows that the GSHP–FC microgeneration system achieved a significant overall energy saving compared to a conventional system that utilizes boiler and chiller to meet the thermal and electric loads of the two buildings. However, in order to thoroughly evaluate the system performance, both energy and cost savings should be considered.

To continue the previous work performed by Entchev et al. [31], this study investigates the performance of GSHP–FC microgeneration systems that serving multiple residential and small office buildings (instead of one house and one small office as studied in Ref. [31]) to approach real-life small neighborhood situations. In addition to the energy analyses, the cost analyses are conducted in order to thoroughly evaluate the performance of each studied system. The energy and cost performance of four GSHP–FC systems (with various FC capacities) are compared to a GSHP only system. It is expected that whether a GSHP–FC microgeneration system is economically feasible compared to a GSHP system is strongly dependent on the local natural gas and electricity prices and also on the building heating, cooling and electrical loads and their patterns. Therefore, the impact of the geographic location, FC capacity, utility prices (natural gas and electricity prices) and their billing structures on the system's energy and cost performance is examined in this study.

It should be noted that there are considerable amount of interests in the optimization of distributed energy resources. The cost optimization of a network of micro combined heat and power systems at the neighborhood level is examined by Kopanos et al. [32] and the annualized overall investment and operating cost of a variety of competing microgeneration technologies is minimized [28]. However, the present study focuses on the energy and cost analyses of a centralized GSHP–FC system. The optimization of the investigated hybrid microgeneration systems and the inclusion of multiple distributed microgeneration resources within a microgrid will be considered in the future study.

2. Hybrid renewable microgeneration system for study

The hybrid renewable microgeneration system investigated in this study is a ground source heat pump with a natural gas fueled proton exchange membrane fuel cell (PEMFC) as shown Fig. 1. The system uses a water-to-water ground source heat pump as well as the thermal energy from the fuel cell to meet the heating and cooling demand of a building cluster mixed with detached residential houses and small office buildings. The desuperheater of the GSHP is used to preheat the city water for domestic hot water (DHW) use. A hot water storage tank with three immersed heat exchangers stores heat for both space and DHW heating use. The three immersed heat exchangers are used to transfer heat from the GSHP to the tank, from the FC to the tank, and from the tank to the building heating coils respectively. A natural gas burner located at the bottom of the hot water tank provides supplementary heat in cases where additional heat is needed in very cold days or in summer season (for DHW heating). A tempering valve is installed in the DHW system to stabilize the supply temperature. A cold water storage tank with an immersed heat exchanger is used to deliver chilled water to the cooling coils in summer season. The FC generated electricity is used by the buildings and their HVAC systems to offset the electricity import from the grid. Excess electricity produced by the FC, if there is any, is exported to the grid.

The immersed heat exchangers that deliver heat to the hot water storage tanks are located near the bottom of the tank to ensure best conditions for optimal heat transfer. For the cold water storage tank, the immersed heat exchanger is located near the top to keep the tank well stratified as well as to leave some storage volume for the chilled water at the tank bottom.

The microgeneration GSHP–FC system is assumed to serve a small building cluster consisting of five identical detached residential houses and two identical small office buildings to investigate the practicability of these systems in serving different number and type of buildings. The houses and offices are one-story buildings. While each house has a floor area of 200 m^2, each office has a floor area of 500 m^2. The building specifications meet the minimum building envelope requirements for climate zone 4 recommended by ASHRAE Standard 90.1-2007 [33].

The performance of the GSHP–FC system is compared to a ground source heat pump only system to assess its effectiveness. The configuration of the latter system is the same as the former system as shown in Fig. 1 except without a FC unit.

3. Analysis methodologies

3.1. Energy analysis methodology

TRNSYS platform, a flexible graphically based software environment for simulating the behavior of transient systems such as thermal and electrical energy systems [34,35], was used in the present study. Majority component models were selected from the TRNSYS libraries and enhanced with latest manufacturers' performance data. A custom fuel cell model was developed by using empirical-based non-linear regression method and validated by experimental data for a PEMFC tested at CanmetENERGY facility [22]. Summary of the model types used in the simulations and verifications are presented in Ref. [31].