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Simulation of hybrid renewable microgeneration systems in load sharing applications

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ABSTRACT

This study investigates the performance of hybrid renewable microgeneration systems in load sharing application between a detached residential house and a small office building. Two renewable energy systems are investigated: a ground source heat pump (GSHP) system and a hybrid GSHP/fuel cell (FC) system. The renewable systems performance is compared to a conventional system that utilizes boiler and chiller to meet the thermal loads of the two buildings. Models are developed for the three selected systems and then simulated in TRNSYS-17 environment over one full year under Ottawa, Canada weather conditions.

The simulation results showed that, by implementing a single GSHP system able to meet both heating and cooling loads of the buildings, an overall energy saving of 39% can be achieved mainly due to the introduction of a significant renewable component. The integrated hybrid GSHP–FC system results an overall energy saving of 24%. However, the hybrid GSHP–FC system generates additional electricity and based on the energy pricing structure can lead to more significant cost savings. Additionally, the GSHP–FC microgeneration system's capability to generate both heat and power at the point of use is considered more attractive for new and remote community applications and for inclusion in the "smart" grid 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 kW_e) mainly due to the high efficiency performance, good environmental footprint and suitability to serve as both primary and back-up power generation [2–30]. 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 [31,32].

Despite some similarities, there is a significant difference the way a microgeneration system operates in comparison to large combined heat and power (CHP) systems, both in terms of technology, cost, social and environmental constraints. Micro CHP can help to meet a number of energy and social policy aims and there are a reduction of green house gas emissions, enhanced energy security and possible avoidance of energy losses from electricity transmission and distribution networks [33,34]. Microgeneration systems in size of 1–30 kW_e and less than 50 kW_{th} are able to provide all or part of the power and heating loads required by a typical building or a group of buildings and can be incorporated in "smart" grid applications. Most of the systems are suitable for both on-grid and off-grid applications. In either case, heat produced during the electricity generation can be recovered and used to satisfy space and water heating of the building in winter and to provide in some cases thermal cooling in summer. Although micro-CHP 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.

In recent years, numerous researches have been conducted on development, design guidelines, experimental testing, energy, cost

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and emission analyses, and optimization of micro CHP systems that based on different technologies, such as micro-turbine [4,5], internal combustion engine [6–11], organic Rankine cycle [4,12,13], Stirling engine [6,14–16], photovoltaic thermal (PVT) [6,17,18], and fuel cell [5,17,19–30]. Fuel cell based micro CHP systems gained a wide range of interests due to their potential to operate with higher electrical efficiency. Among these micro CHP researches, most were focused on one technology or comparison of different technologies. Some researchers [9,12–14,18,21] have studied hybrid micro CHP systems with integration of renewable energy. Gusdof et al. [9] reported experimental results of a residential tri-generation CHP system with an IC engine and ground source heat pumps (GSHPs). Tempesti et al. [12] and Guo et al. [13] investigated organic Rankine cycle system powered by low-temperature geothermal resource. Ribberink et al. [14] analyzed and compared micro CHP systems with a Stirling engine and solar collectors. Obara et al. [18] examined a completely energy-independent micro-grid consisted of photovoltaic, water electrolyzers, proton-exchange membrane fuel cell (PEMFC) and heat pumps. Calise et al. [21] studied polygeneration systems with PEMFC, solar heating and LiBr–H_2O chiller. Only few have studied hybrid systems with integration of FC and geothermal source [27–30]. Bendaikha et al. [27,28] investigated the performance of two hybrid FC-geothermal source systems for school canteens in Algeria. In these two hybrid systems, while the heat generation from the PEMFC and geothermal source were used for heating, the cooling was provided by the air conditioning sub-system made of a fan coil and a heat pump [27] or a LiBr/H_2O absorption chiller [28] with cool water tank. Ratlamwala et al. [29] have undertaken a thermodynamic analysis of a system that integrated PEMFC and triple effect absorption refrigeration system with geothermal water source to meet building heating/cooling and power demand. The hybrid energy system study (HESS) II project [30] was to explore the potential efficiency improvements that could be made to a hybrid residential/commercial heating/cooling system (located in an annex to the Quarry Hill Nature Center, Rochester, Minnesota) by combining a commercially available reversible geothermal heat pump system with a low-grade heat generation from a PEMFC and stratified thermal storage tanks [30]. The results of the HESS project confirm the viability of using stored low grade heat as a heat pump thermal source in heating mode as well as the improved heat pump performance possible in such conditions [30].

In residential houses the main thermal loads occur in the evening through the early morning, while in offices the main thermal loads occur during the daytime, office hours [16]. Typically, a separate heating/cooling equipment is used to meet the loads. The systems are sized to meet the buildings design load conditions that occur less than 1% of the time [35] thus forcing the equipment to operate at low efficient part load state in majority of the time. However, if two buildings with different load profiles are combined together, a single HVAC system can be used to supply both heating and cooling to them. In this case, the combined system will have a better utilization factor and will operate more efficiently with better environmental footprint.

Currently, Annex 54 of the International Energy Agency's Energy Conversion in Buildings and Community System Programme (IEA/ECBCS) is undertaking an in depth analysis of microgeneration and associated other energy technologies [36]. 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 [36].

The present study was conducted in order to contribute towards the improvement of hybrid renewable microgeneration system in load sharing applications. In this paper three systems that able to meet both heating and cooling loads in a load sharing application between a single detached house and a small office building are studied. The first system is a conventional system with single boiler and chiller, the second one is a ground source heat pump system and the third one is a hybrid renewable micro trigeneration system (i.e. integrated heating, cooling and power generation system) with fuel cell and ground source heat pumps. The objective of this study is to model, simulate and analyze the performance of the hybrid renewable GSHP–FC microgeneration system.

2. System configurations for case studies

The house and office buildings simulated in the present study are separated from each other where there is no any thermal interaction between them. The two one-story buildings have the same geometries with a floor area of 200 m^2. The building's height is 2.7 m and the window to wall area ratio is 22%. The overall heat transfer coefficient has a value of 0.54, 0.351, 0.283 and 1.69 W/m^2 K for the roof, external wall, floor and windows respectively typical for "average" Canadian houses [37].

Three different scenarios/cases are investigated in the present study: The first case is a conventional load sharing setup where a single unit of boiler and chiller is used to satisfy the heating/cooling loads of the house and the small office building. Case 1 is assumed as a reference system in the study. The second case utilizes a ground source heat pump (GSHP) system to meet the thermal energy demands of both buildings. The third case uses a hybrid renewable microgeneration system with a GSHP and a fuel cell (FC) to supply heating/cooling energy and electricity to the house and office building. The schematic of the three systems is shown in Fig. 1(a)–(c).

In Case 1 (Fig. 1a), the shared boiler and chiller are located outside of the buildings and the hot/chilled water is delivered through pipes to the fan-coils units installed inside. Domestic hot water (DHW) needs are met by separate storage tanks in each building.

In Case 2 as shown in Fig. 1b, a water-to-water ground source heat pump system is used to meet both the heating and cooling requirements of the two buildings. The desuperheater (DSH) of the GSHP is used to preheat the city water for DHW use. A hot water storage tank (HWST) with two immersed heat exchangers stores the heat for both space and DHW heating use. The tank supplementary burner compliments the GSHP operation in cases where additional heat is needed. A cold water storage tank (CWST) with an immersed heat exchanger is used to provide chilled water to the cooling coil in summer season.

The hybrid GSHP–FC microgeneration system (Case 3) configuration as shown in Fig. 1c is similar to Case 2, except an additional immersed heat exchanger is added to the hot water storage tank for utilizing the residual heat from the FC. The electricity generated by the FC is used in the two buildings to offset the electricity import from the grid. Similar to Case 2, a gas burner located at the bottom of the hot water tank provides supplementary heat in cases where the GSHP and FC are not sufficient in very cold days or in summer season (for DHW heating).

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.

Table 1 presents a summary of the modelling cases and corresponding energy technologies used for space heating/cooling and DHW heating.